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D1/57

DAMAGE BY NUCLEAR WEAPONS

A MANUAL OF BASIC TARGET RESPONSE DATA

SECURITY NOTE

This document has been issued in parts over an extended period and much of the earlier material now has a lower classification than it carried at the time of issue. Notwithstanding the grading shown on individual sheets dated earlier than March, 1959, the whole of the contents are now covered by the grading CONFIDENTIAL DISCREET.

Prepared by the Director General of Atomic Weapons
Ministry of Aviation.

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DAMAGE BY NUCLEAR WEAPONS

Amendment Certificate.

Amendment List Number	Date	Amendments Made By	Date
1			
2	7-9-60	M. L. Moore	7-9-60
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DAMAGE BY NUCLEAR WEAPONS

LAYOUT OF THE MANUAL

PART	CONTENTS
I	INTRODUCTION
II	GLOSSARY, DEFINITIONS, UNITS OF MEASUREMENT
III	DAMAGE BY AIR BLAST
IV	DAMAGE BY CRATERING AND EARTH SHOCK
V	DAMAGE BY SURFACE WAVES AND UNDERWATER SHOCK
VI	DAMAGE BY THERMAL RADIATION
VII	DAMAGE BY NUCLEAR RADIATION
VIII	MISCELLANEOUS
	BIBLIOGRAPHY
	INDEX

A more detailed list of contents will be found at the beginning of each part.

D1/57
Revised
February, 1960.

Part I
Preliminary

DAMAGE BY NUCLEAR WEAPONS

PART I - INTRODUCTION

CONTENTS

1. Scope of Manual

2. Damage Mechanisms

3. Target Response to Individual Effects

4. Target Response to Conjoint Effects

5. Accuracy of Data and Analysis

6. Sealing Laws

7. Sources of Further Information

8. Acknowledgments

9. Errors and Omissions

Appendix A. Preparation and use of Target Damage Charts (Figures 1 and 2).

PART I - INTRODUCTION

1. Scope of the Manual

This Manual is intended to facilitate the estimation of damage by nuclear weapons. A nuclear explosion produces a blast pressure wave; electro-magnetic radiations throughout the ultra-violet, visible, infra-red, and radio spectra; and both initial and residual nuclear radiations. The interaction of each of the above effects with a variety of targets is considered in this Manual, and criteria are given for the resultant damage. Some trials results are quoted for comparison with theory.

Computation of the damage caused by a nuclear explosion is normally divided into several stages. One must estimate in turn:-

(a) The magnitude of the physical effects - blast, heat, etc. - produced by the explosion.

(b) The propagation of these effects from the vicinity of the burst to that of the target.

(c) The response of the target to the physical effects incident upon it. It is sometimes necessary to make allowances for changes in these effects due to the presence and reaction of the target itself.

For details of the weapon effects as a function of distance, weapon yield and burst conditions, readers are referred to the A.W.R.E. Manual on the Effects of Atomic Weapons (short reference M.E.A.W.), Reference (1). An alternative unclassified source of weapon effects data is the Effects of Nuclear Weapons (short reference E.N.W.), Reference (2).

The object of this Manual is to assist in applying such data to practical problems by discussing the response of targets and the methods of analysis.

2. Damage Mechanisms

As this Manual is concerned equally with the assessment of damage to existing targets, and with the principles involved in minimising or maximising the damage in future situations, some preliminary attention must be given to damage mechanisms. In practice, these mechanisms may operate either singly or together. In the latter case, analysis of the response tends to become more difficult, occasionally intractable, and it is fortunate that the individual mechanisms can often be estimated separately. The extent to which this may be assumed to be the case depends upon the burst conditions and range, as well as upon the target. To assist in identifying the damage mechanisms in a particular case, reference should be made to Figure 1 for Air Bursts, and to Figure 2 for Surface Bursts, in Appendix A at the end of Part I. It is emphasized that these diagrams are intended primarily to indicate orders of magnitude of the effects and of their rates of variation with range. In the interests of simplicity, the diagrams necessarily embody assumptions which may invalidate their exact application to a particular operational or technical situation. They should however, enable the reader to determine for a wide range of targets whether the predominant damage is likely to be due to blast or to thermal or nuclear radiation etc., and thus to avoid irrelevant analysis. It must be remembered that all the parameters concerned are subject to appreciable uncertainties in practice, so that alternative effects cannot be neglected unless they are considerably less than those required for damage of equal importance, at the same range as that considered for the main effect.

Curves have not been drawn for underground or underwater bursts, which are rather specialised cases needing detailed treatment - given in Parts IV and V respectively. Note that situations may occur where these special effects may arise almost fortuitously, e.g. phenomena of base surge and wave formation may be of major importance to land targets in the case of an off-shore burst near a port or harbour installation, or of an inland burst in water. Details of the method of use of these charts, and of the assumptions made in their preparation, are given alongside the charts in Appendix A.

3. Target Response to Individual Effects

If a single paramount effect can be identified as above, the appropriate part of the Manual may be consulted for a brief description of the transport of the particular form of energy to the vicinity of the target, the phenomena attendant upon its absorption or scattering by the target, and the nature and scale of the resultant damage. Critical levels of individual incident effects for various defined degrees of damage are quoted for the widest possible variety of targets. Comparisons of results from full-scale trials, model or laboratory scale experiments and theoretical studies, are included where available.

Attention is given to the methods of calculation of actual target response from the point of view of readers whose main interest is to proceed from an appreciation of the likely fate of existing targets to an understanding of the results of changes of design or of construction. In several cases the complete phenomenon is too complex for rigorous analysis, and stress is then laid on limits of validity of any simplifying assumptions which must be made.

4. Target Response to Conjoint Effects

Throughout most of this Manual each effect is treated as if it alone were affecting the target. This leads to negligible loss of accuracy in cases where the response to one effect predominates, e.g. a target which has burnt up before arrival of the blast wave. In any cases where the data given in the Manual lead initially to comparable probabilities of damage by more than one mechanism, the practical situation should be examined with care to determine all relevant factors, and in particular, where one effect is modified by the presence of others. This is of particular importance in the case of biological targets, e.g. the enhancement of post-burn shock by that consequent upon nuclear irradiation.

Results derived from full-scale trials are included where available as a general guide to the nature of the response of the target in question. It is urged that for the present, such results be treated with appropriate reserve, as details of damage have only rarely been stated, and in many cases the precise conditions at the trial may be in significant doubt. Such results may provide valuable statistical data on existing targets, but are of limited reliability in assessing the likely effects of modifications. It must also be remembered that most nuclear trials are held in places where the terrain is very different from that to be expected in the majority of campaigning areas, and the effects of vegetation or of extensive built-up areas of Western type can only be conjectured.

5. Accuracy of Data and Analysis

Where known, indications are given of the accuracy to be expected of the data and of the techniques of analysis. In many cases this is hard to judge, and no statement is therefore made. The reader is urged to remember the imprecise nature of the problem, and hence to avoid carrying analysis to unjustified lengths. Under operational conditions the

yield and burst conditions of individual weapons may differ significantly from those assumed, as may the propagation conditions from weapon to target. It is also very difficult to generalise about the targets themselves. Practical targets may vary by large factors, which depend upon individual materials and techniques of construction, age, etc., rather than on design. Biological targets are also subject to very large standard deviations in their response. Thus the overall practical accuracy to be expected will rarely be better than some tens per cent, and may be correct only in order of magnitude in some cases. Refined calculations are rarely justified, and somewhat crude approximations are frequently permissible. The important point is that the basic phenomena should have been sufficiently well understood for the relevant variables to have been identified, and for the extent of applicability of any approximations to be defined.

6. Scaling Laws

It is often possible to infer from the results of a given explosion the results of larger or smaller explosions, in accordance with the normal rules of dimensional analysis. The application of this in relation to pressure effects is the analytical technique variously named Stress Modelling, Equi-velocity Modelling, Mach Modelling, and also known in the field of high explosives research as the Hopkinson Scaling Laws. It is often referred to briefly as "cube root scaling".

The rules relating corresponding parameters of an explosion of power W to those of a reference explosion of power W_o are as follows:-

Times	Scale as $(W/W_o)^{\frac{1}{3}}$
Distances	Scale as $(W/W_o)^{\frac{1}{3}}$
Velocities	Are invariant
Densities	Are invariant
Accelerations	Scale as $(W/W_o)^{-\frac{1}{3}}$

It will be seen that acceleration is not invariant with weapon yield, so that these laws cannot apply at all exactly to phenomena in which gravity plays an important part. An obvious example is cratering. It is also common to find that in practice, times scale with $W^{\frac{1}{2}}$ rather than $W^{\frac{1}{3}}$, e.g. thermal pulse length. The complexity of some of the processes involved in nuclear explosions in a non-homogeneous medium are such that empirical scaling rules are commonly used. In view of the complexity and limited reproducibility of many of the phenomena concerned both in weapon effects and in target response, simple power law expressions are often used, e.g. $W^{0.4}$ for damage ranges in the case of many types of target. Such laws are quoted in the relevant section of the Manual. It must be noted that considerable caution is required when using these empirical relationships for purposes of gross extrapolation.

7. Sources of Further Information

As it is clearly impossible for a publication of this nature to deal fully with every, or indeed any problem, or to be completely up-to-date, the contributors to the various sections have expressed themselves willing to assist with enquiries on specific points. In cases not covered by the following list the Editor may be able to assist by introducing inquirers to the appropriate experts.

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9. Errors and Omissions

The Editor would much appreciate having any errors and omissions brought to his attention.

10. References

(1) A.W.R.E. Manual on the Effects of Atomic Weapons

(2) "The Effects of Nuclear Weapons" United States Government Printing Office (also published by H.M.S.O.) June, 1957.

PREPARATION AND USE OF FIGURES 1 AND 2
TARGET DAMAGE CHARTS

1. Introduction

Figures 1 and 2 present target damage data for air and surface bursts respectively.

Each chart consists of a rectangular diagram divided off vertically and horizontally into logarithmic scales. The ordinate scale is marked on left and right-hand sides in total yield of the bomb, from 1 kiloton to 100 megatons. The horizontal scales at top and bottom are marked in thousands of feet, and cover from 400 feet to 300,000 feet. For ease of conversion, subsidiary parallel range scales in statute miles, nautical miles and kilometres, are provided.

For the present purpose, the response of a target is defined in terms of one or more of the following five parameters:-

1. Blast overpressure (squeezing effect); lb. per sq. inch (p.s.i.).
2. Blast dynamic pressure (gust effect); lb. per sq. inch (p.s.i.).
3. Thermal radiation dose; calories per sq. centimetre (cals/cm ^{2}).
4. Initial gamma dose; roentgens (r).
5. Neutron dose; neutrons per sq. centimetre (n/cm^2) for materials,
   roentgen equivalent mammal (r.e.m.) for biological purposes.

In the case of an air burst, the fallout hazards and induced ground activity are very limited and are therefore not included in Figure 1.

2. Use of the Figures

Owing to the log/log scaling, the target damage curves showing the range at which a given damage criterion first becomes critical for a given yield of bomb, are very nearly straight lines. Some of these, likely to be of general interest, have been inserted in the diagram. Further lines can be inserted by the user, with the help of the subsidiary scales labelled in terms of the five parameters mentioned above. In the case of the blast pressures and the thermal or neutron dose, it is necessary only to mark off the critical values on the two scales at the top and bottom of the diagram and to connect them by a straight line. In the case of initial gamma doses, a straight line is inappropriate because the blast wave reduces the atmospheric attenuation of the radiation at high yields. The curve can however, be reproduced to a sufficient accuracy by two straight lines, from the top to the centre of the diagram and from the centre of the diagram to the bottom. The dose curves for 10^4, 10^5, and 10^6r have been reproduced in full.

3. Assumptions

The curves plotted in this way represent some simplification. The basis of their preparation is given briefly in the notes below.

3.1 Blast curves

Ranges are plan ranges, and the dynamic pressure is due to the horizontal component of the blast. These curves are based on average conditions including some precursor. Between 100 p.s.i. and 2 p.s.i. overpressure, and for all dynamic pressures, the height of burst assumed is that which maximises the radius of damage for the particular pressure concerned, i.e. the 10 p.s.i. curve is computed on the assumption that the height of burst had been chosen to maximise the range at which 10 p.s.i. occurs. However, since it is unlikely that a height of burst would be chosen to maximise still lower pressures in this way, the 1.5 and 1 p.s.i. curves are based on a height of burst which would have maximised 10 p.s.i.

3.2 Thermal curves

Ranges quoted for thermal curves are slant ranges in the case of Figure 1. The thermal energy release is assumed to follow the law –

$E = 0.36W$ in the case of air bursts, and

$E = 0.147W$ for surface bursts

where W is the total yield in kilotons. The mean visibility correction for 2 – 50 miles visibility (British M.E.A.W.), is employed.

3.3 Ball of Fire

The maximum radius of the ball of fire shown for air bursts is based on the expression:-

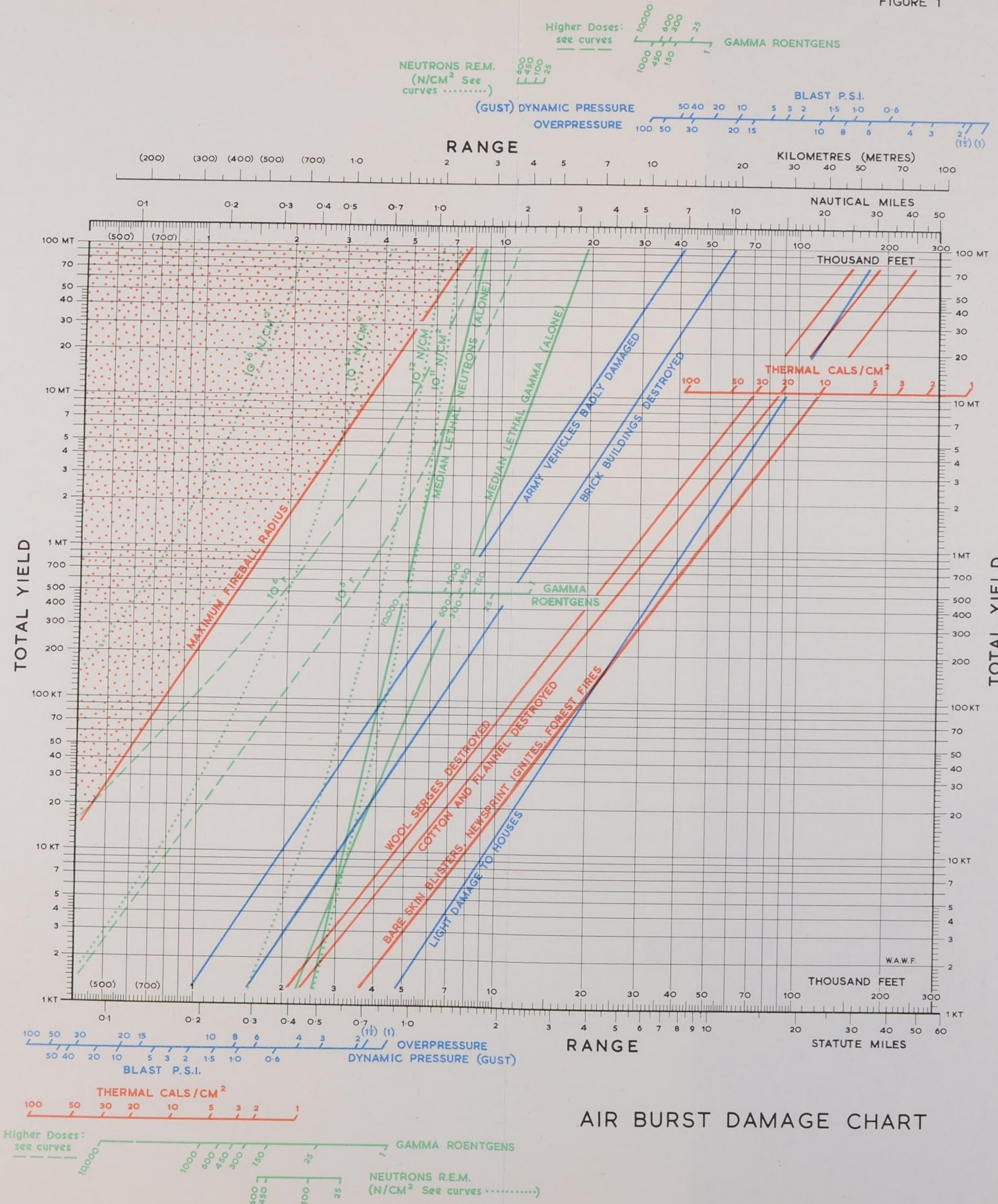
$R = 166\,W^{1/3}$ for air bursts,

$R = 190\,W^{1/3}$ for surface bursts,

where R is in feet, and W is the total yield in kilotons.

Continued on next sheet (Fig.2)

PART I
FIGURE 1



AIR BURST DAMAGE CHART

Continued from previous sheet (Fig.1)

3.4 Gamma curves

Ranges quoted are slant ranges in the case of air burst. The attenuation of the gamma radiation by the air is reduced in the case of large yield weapons by the rarefaction which occurs behind the blast wave.

The rarefaction correction is introduced by scaling the yield as follows:

True Yield KT	1	3	4	10	30	40	100	300	400
Scaled Yield Air Burst	1	3	4	10	34	46	148	655	920
Scaled Yield Ground Burst	1	3	4	10	35	48	150	720	1160
True Yield MT	1	3	4	10	30	40	100		
Scaled Yield Air Burst	3.8	18	32	82	310	400	–		
Scaled Yield Ground Burst	4.7	25	39	160	850	1360	5600		

A correction is also made in the case of air bursts for the variation in atmospheric density with height, according to the formula –

$$R = (p_h - p_o)/\sigma_o h$$

R is the assumed relative density

p_h and p_o are the pressures at height of burst h and at ground level respectively and σ_o is the ground level air density. The height of burst assumed for the air burst is rounded off from that which optimises 10 p.s.i. overpressures.

3.5 Neutron Dose Curves

The neutron output from a bomb may vary considerably with the design; in general it is greater, in relation to yield, in the case of small weapons than it is for large ones.

Some curves giving typical intensities at various slant ranges are shewn for Air Bursts in Figure 1. The same curves may be used to a sufficient approximation for surface bursts. Their primary use is for guidance when considering the response of materials and components such as transistors, photographic materials, explosives, special organic compounds etc.

The medical r.e.m. curves are based upon similar assumptions about neutron output. The ranges are slant ranges in the case of Figure 1, (Air Bursts). Some correction has been made for the variation in attenuation with atmospheric density.

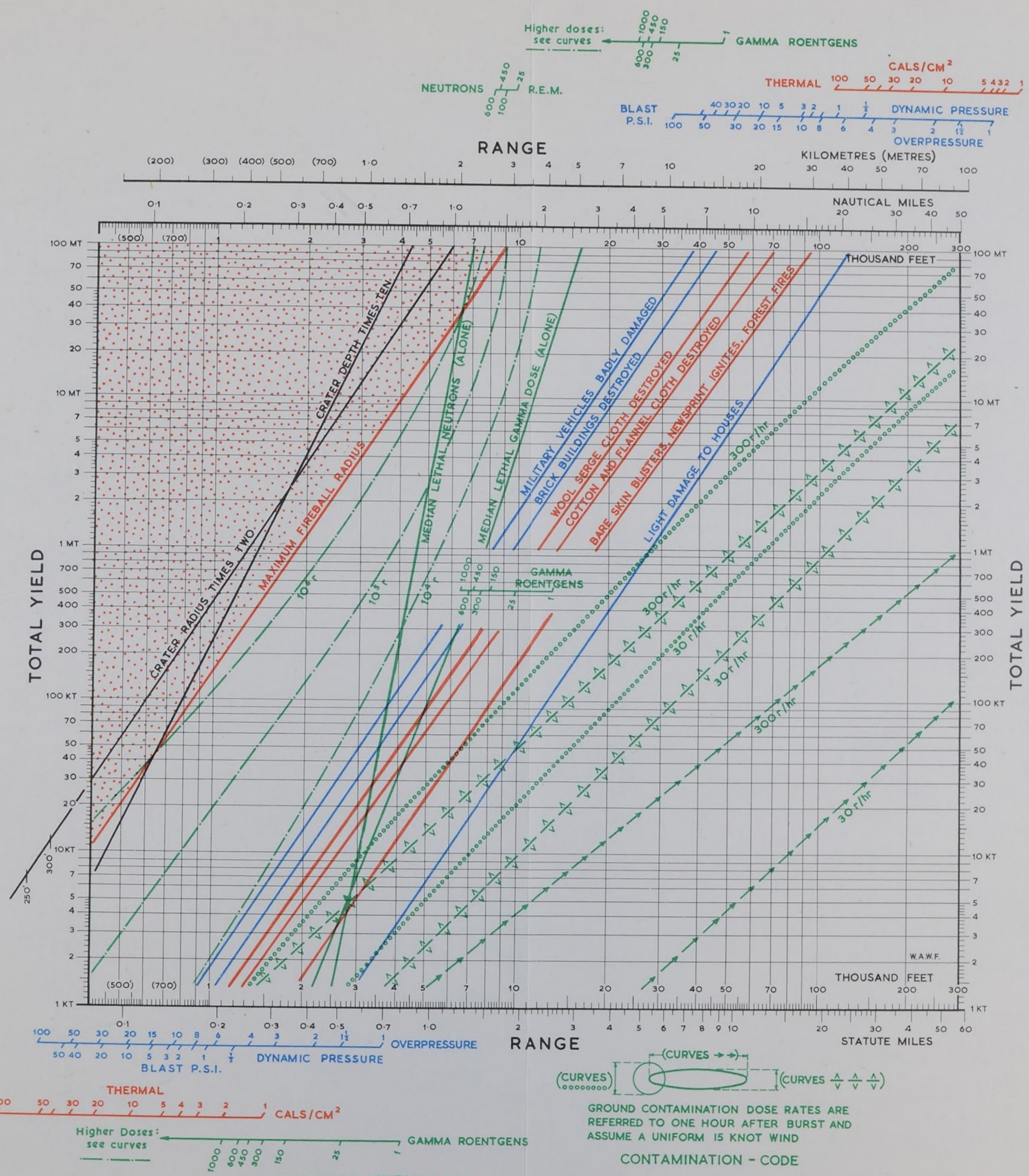
3.6 Response curves

A number of typical response curves have been inserted by way of illustration. The values chosen are a simplification from known data as follows:-

	KT		MT
Second Degree Skin Burns	3½	–	8 cals/sq.cm.
Forest Fires	3	–	10 cals/sq.cm.
Newspaper and Dead Leaves Ignite	3½	–	10 cals/sq.cm.
Cotton and Wool (flannel) Destroyed	10	–	20 cals/sq.cm.
Wool Serges Destroyed	13	–	30 cals/sq.cm.
Army Vehicles (heavy, medium and light) Badly Damaged			5 p.s.i. dynamic
Brick Houses Collapsed			10 p.s.i. overpressure
Brick Houses Lightly Damaged			2 p.s.i. overpressure
Gamma 50% Lethal Dose			450 roentgen
Neutron 50% Lethal Dose			450 r.e.m.

The irradiation doses are based on the assumption that each is acting on its own. Light house-damage is minor structural damage – windows may be broken at much lower pressures. Vehicular damage is based on over-turning and major breakage rather than total loss.

For method of insertion of curves based on other criteria, see Section 2 of this Appendix on preceding chart.



SURFACE BURST DAMAGE CHART

PART II - GLOSSARY

Note

As this Glossary is intended for the assistance of users of this manual, the entries are more in the nature of explanations than of definitions. The appropriate references should be consulted when authoritative definitions are required.

Block Capitals in the text denote Glossary items.

ABSORPTION	The removal of radiation or the reduction of its energy by means other than scattering, on passing through matter. Sometimes used to mean CAPTURE.
ABSORPTION COEFFICIENT	Of a uniform substance for a parallel beam of radiation, the quantity in the expression $e^{-\mu x}$ which gives the fraction remaining unabsorbed after passing through a layer of thickness x. The thickness may be given in units of 1 cm, 1 g/cm^2, or 1 mole/cm^2; accordingly μ is called the linear, mass, or molar absorption coefficient of the absorber for the radiation in question.
ABSORPTION CURVE	A graph of the intensity of the transmitted radiation plotted against the absorber thickness.
ABSORPTION SPECTRUM	A graph of absorption as a function of energy or wavelength. Often used figuratively.
ACTIVATION	The process of inducing radioactivity.
ACTIVITY (see CURIE)	The number of disintegrations per unit time taking place in a radioactive specimen.
ACUTE DOSE	See under Chronic Exposure.
AIR BURST	See under CATEGORIES OF BURST.
AIR DOSE (FREE-AIR DOSE, IN-AIR DOSE)	A dose of radiation, measured in air, from which secondary radiation (apart from that arising from the air, or associated with the source) is excluded.
AIR EQUIVALENT	Of a given absorber, the thickness of a layer of air at standard temperature and pressure which causes the same absorption or energy loss.
AIR EQUIVALENT MATERIAL (AIR-WALL MATERIAL)	A material, suitable for the walls of IONIZATION CHAMBERS and having substantially the same effective atomic number as air.
AIR SCATTER (SKY-SHINE)	That radiation which is scattered downwards from the air or structures above a source of radiation and so continues to reach an observer in spite of shielding placed between him and source.
ALBEDO	The ratio which the diffuse radiation reflected from a surface bears to the total radiation of the same type incident upon it from all angles. This ratio depends upon the nature and energy of the radiation.

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ALLOBARS	Forms of an element having a different isotope composition, and therefore a different atomic weight, from the naturally occurring form.
ALPHA PARTICLE	A fast moving helium (^4He) nucleus. It thus has mass 4, charge plus 2 units.
ÅNGSTRÖM UNIT (Å.U.)	Length unit ($\approx 10^{-8}$ cm) used mainly in spectroscopy. 10^4 Å.U. = 1 micron.
ANNIHILATION (PARTICLE)	A collision between a particle and its anti-particle (in practice, a positive and a negative electron) in which they both disappear; their energy is (usually) converted into two or three high-energy photons.
ATOM	The smallest (or ultimate) particle of an element that still retains the chemical characteristics of that element. Every atom consists of a positively charged central nucleus which carries nearly all the mass of the atom, surrounded by a number of negatively charged electrons, so that the whole system is electrically neutral. An atom which loses its neutrality becomes an ion.
ATOMIC CLOUD	An all-inclusive term for the mixture of hot gases, smoke, dust and other particulate matter from the bomb itself and from the environment, which is carried aloft in conjunction with the rising ball of fire produced by the detonation of a nuclear weapon.
ATOMIC ENERGY	See NUCLEAR ENERGY.
ATOMIC MASS	The mass of a neutral atom of a nuclide which is usually expressed in atomic mass units, amu.
ATOMIC NUMBER	Of an element: the integer Z, where Ze is the nuclear charge and e is the charge of a proton.
ATOMIC WEIGHT	For a given specimen of an element; the mean weight of its atoms, expressed either in atomic mass units (physical scale) or atomic weight units (chemical scale).
ATTENUATION	Reduction in intensity (of a particular form of energy) by passage through any medium.
BACKGROUND	Of a counter (emulsion etc.). The counting rate (track density) in the absence of the radiation which it is specifically meant to measure.
BACKGROUND MONITOR	A monitor used to give indication of the prevailing level of background radiation.

BACKGROUND RADIATION (NUCLEAR) — Nuclear radiations arising from within the body and/or from the surroundings to which individuals are always exposed. The main sources of the natural background radiation are cosmic rays, local gamma rays from rocks and organic materials and radon in the air, and beta radiation from potassium-40 in the body, according to the situation.

BACK SCATTER FACTOR — 1. In dosimetry, the factor by which the dose rate at a point in a beam of radiation is increased when that point lies on the surface of a body being irradiated.
2. In counting, the factor by which the counting rate is increased by the fact that additional particles are scattered back by the source material and its support.

BACK-SCATTERING — The emergence of radiation from that surface of a material through which it entered.

BALL OF FIRE (FIREBALL) — The luminous sphere of hot gases which forms a few millionths of a second after a nuclear explosion, and immediately starts to expand and cool. The exterior of the ball of fire is initially defined by the luminous shock front (in air) and later by the limits of the hot gases themselves. (See BREAKAWAY).

BARN — A unit of CROSS-SECTION (origin jocular, from "as big as a barn").

1 barn (b) = 10^{-24} cm^2
1 millibarn (mb) = 10^{-27} cm^2

BASE SURGE — A cloud which rolls outward from the bottom of the column produced by a sub-surface explosion. For underwater bursts the surge is, in effect, a cloud of water droplets with the property of flowing almost as if it were a homogeneous fluid, to which normal terminal velocity considerations do not apply.
For sub-surface land bursts, the surge is made up of small solid particles, but it still behaves like a fluid. A soft earth medium favours base surge formation in an underground burst.

BETA PARTICLE — An electron (more rarely a positron) emitted spontaneously from a radioactive nucleus. Most of the fission fragments emit negative beta particles.

BETA PROCESS — (See BETA TRANSFORMATION.)

BETA RAYS — Originally rays intermediate in penetrating power between alpha and gamma rays, soon identified as electrons. Nowadays radiation composed of beta particles.

BETA TRANSFORMATION (BETA PROCESS)	The transformation of a nucleus into its neighbouring nuclear isobar, with the emission of a positive or negative electron, or with the capture of an orbital electron.
BIOLOGICAL HALF-LIFE	The time required for half a specimen of a particular substance to be removed from the body or from a specified tissue by biological means, when the rate of removal is approximately exponential. Note distinction from EFFECTIVE HALF-LIFE.
BLAST EQUIVALENT	That weight of high explosive which, detonated at the same point as a nuclear explosion, would produce identical blast effects at the point of observation. The Blast Equivalent depends upon energy partition, mechanism of propagation, and target.
BLAST LOADING	The loading (or force) on an object caused by the air blast from an explosion striking and flowing around the object. It is a combination of overpressure (or diffraction) and dynamic pressure (or drag) loading.
BLAST SCALING LAWS	Formulae which permit the calculation of the properties, e.g. overpressure, dynamic pressure, time of arrival, duration, etc., of a blast wave at any distance from an explosion of specified energy, from the known variation with distance of these properties for a reference explosion of known energy, e.g. of 1 kiloton.
BLAST WAVE (AIR)	A pressure pulse of air accompanied by winds, propagated continuously from an explosion.
BLAST YIELD	The part of the energy of an explosion that appears as blast energy.
BLOOD COUNT	The determination of the number of the various types of red and white cells per cubic mm. of peripheral blood, by a process involving dilution and actual counting under a microscope.
BODY BURDEN	The total amount of a given nuclide present in the body as a whole at a given moment.
BONE SEEKING ELEMENT (BONE SEEKER)	Any element which in vivo is absorbed preferentially by bone.
BREAKAWAY	The onset of a condition in which the shock front (in the air) first moves away from the exterior of the expanding ball of fire produced by the explosion of a nuclear weapon.
BREMSTRAHLUNG	See RADIATIVE COLLISION.
BROAD BEAM ABSORPTION	Absorption of radiation under such conditions that some or all of the scattered radiation transverses the target or measuring area.
BUILD-UP FACTOR	The ratio of the total intensity of a beam of radiation penetrating a shield, to that of its unscattered component.

CALORIE	The quantity of heat required to raise the temperature of 1 gram of water from 15°C to 16°C at 760 mm. mercury pressure. 10^{-12}KT. 3.966×10^{-3} B.T.U. 4.184 Joules 2.61×10^{-13} Mev. 3.086 Ft.-lbs.
CAMOUFLET	Cavity in the ground, not breaking the surface.
CAPTURE GAMMA RAYS	The instantaneous gamma rays resulting from radiative capture.
CAPTURE, RADIATIVE	The retention of a bombarding particle (neutron, proton, etc.) by a nucleus, with the subsequent emission of gamma-rays whereby the nucleus loses energy so that re-emission of the particle becomes impossible.
CATEGORIES OF BURST	FREE AIR BURST - A burst which is assumed to occur in an infinite airspace. AIR BURST - A free air burst modified by the presence of the earth's surface, but at such a height that the energy partition is unaffected. LOW AIR BURST or NEAR SURFACE BURST - An air burst low enough for the energy partition to be affected and for special effects to appear (e.g. neutron induced ground activity). U.S. usage - lower than the radius of the fireball at maximum luminosity. SURFACE or GROUND BURST - Strictly a burst in which the weapon is detonated at ground level. In U.S. usage it may also cover low air bursts as defined above. CONTACT SURFACE BURST - U.S. usage for a burst at surface level, see above. SHALLOW SUB-SURFACE BURST - An underground or underwater burst, but still retaining a proportion of the characteristics of a surface burst. (Vents to the surface.) DEEP SUB-SURFACE or DEEP UNDERGROUND BURST - A burst at sufficient depth for there to be no direct venting to the surface.
CHAIN REACTION (NUCLEAR CHAIN REACTION)	A number of nuclear transformations, each capable (e.g. through the neutrons it emits) of causing one or more transformations of the same kind. Depending on whether the number of transformations so caused by one transformation is less than, equal to, or greater than unity, the reaction is convergent, self-sustained or divergent.
CHARACTERISTIC X-RADIATION	X-radiation consisting of discrete wavelengths which are characteristic of the emitting element. Characteristic X-radiation arising from the absorption of X- or gamma-radiation is sometimes called <u>fluorescent X-radiation</u>.
CHEMICAL DOSEMETER	A self-indicating device for determining total (or accumulated) radiation exposure dose based on colour changes accompanying chemical reactions induced by the radiation.

CHRONIC EXPOSURE (to radiation)	Exposure(s) sufficiently protracted for the final result to be affected by the overall duration of the irradiation. The converse is true of acute (sudden) exposures.
COMPOUND NUCLEUS	The highly excited nucleus formed as the immediate result of a nuclear collision.
COMPTON EFFECT	The reduction of the energy of a photon by its interaction with an electron. Part of the photon energy is transferred to the electron (Compton electron) and part is redirected as a photon of reduced energy (Compton Scatter). The scattered photon has a wavelength $\lambda_o + \lambda_c(1 - \cos\alpha)$ if scattered by the angle α; λ_o is its original wavelength, $\lambda_c = h/mc = 24.3 \times 10^{-11}$ cm, the Compton Wavelength.
CONDENSATION CLOUD (WILSON CLOUD)	A mist or fog of minute water droplets which temporarily surrounds the ball of fire, following a nuclear detonation in a comparatively humid atmosphere. The expansion of the air in the negative phase of the blast wave from the explosion results in a lowering of the temperature, so that condensation of water vapour present in the air occurs and a cloud forms. The cloud is soon dispelled when the pressure returns to normal and the air warms up again. The phenomenon is similar to that used by physicists in the Wilson cloud chamber and is sometimes called the cloud chamber effect.
CONTACT SURFACE BURST	See under CATEGORIES OF BURST.
CONTAMINATION, RADIOACTIVE	The deposit of radioactive material on the surface of structures, areas, objects or personnel, following a nuclear explosion. This material generally consists of fallout in which fission products and other bomb debris have become incorporated with particles of dirt, etc. Contamination can also arise from the radio-activity induced in certain substances by the action of bomb neutrons.
CONTAMINATION METER	An instrument for measuring localised contamination by radioactive material, or for measuring the amount of radioactivity in samples of liquids.
COSMIC RADIATION	Ionising radiation from unidentified extra-terrestrial sources.
COULOMB SCATTERING (RUTHERFORD SCATTERING)	The scattering of a particle by the coulomb field (Electrostatic field) of a nucleus.
COUNT	1. A pulse that has been registered, corresponding either to an ionising event, or to an electrical disturbance (spurious count). 2. The number of pulses recorded in a specified period.
COUNT (COUNTING) RATE	Number of counts per unit time.

COUNTER A device which reacts to individual ionising events, thus enabling them to be counted. The term is also loosely used to describe a complete counting equipment.

CRITICAL ENERGY (THERMAL) The minimum quantity of heat energy per unit area for a given weapon yield which is necessary to produce a defined change in a given material, e.g. charring, melting, burning; expressed in units of cals/sq.cm. for weapons of a given yield.

CRITICAL MASS The mass of fissile material that will just maintain a fission chain reaction under precisely specified conditions. These conditions include the nature of the material and its purity, the nature and thickness of the tamper (or neutron reflector), the density (or compression), and the physical shape (or geometry). For a nuclear explosion to occur the system must become supercritical, i.e. the mass of material must exceed the critical mass under the existing conditions.

CROSS-SECTION Of a given nucleus for a given radiation: that area perpendicular to the direction of the radiation which one has to attribute to the nucleus to account geometrically for its inter-action with the radiation. The Total (or Collision) Cross Section which accounts for all inter-actions, is sub-divided into the Elastic Cross Section which accounts for Elastic Scattering and the Inelastic (or Non-Elastic) Cross Section which accounts for all other inter-actions. Further sub-division of the latter is made to account for specified inter-actions as in Inelastic Scattering Cross Section, Absorption (or Capture) Cross Section, Fission Cross Section, etc. The cross section usually varies with the energy of the radiation; its value at any one of the maxima attributed to resonance is called Resonance Cross Section. The Scattering Cross Section can be further specified as referring to radiation scattered through a particular angle between θ and $\theta + d\theta$; it is then written $\sigma_d(\theta) d \cos\theta$ where σ_d is the Differential Cross Section. In Diffusion Theory one obtains correct results, irrespective of the angular distribution of scattering if one replaces the Scattering Cross Section by the Transport Cross Section defined as:

$$\sigma = \int \sigma_d (\theta) (1 - \cos\theta) \, d \cos \theta$$

CRYSTAL COUNTER A counter dependent for its action on a crystal (e.g. diamond) in which the electrical conductivity is momentarily increased by an ionising event. (Not to be confused with Scintillation Counter).

CURIE A measure of the radioactivity emitted by a given quantity of any radioactive material. A sample having an activity of 1 Curie undergoes 3.7 times 10^{10} disintegrations per second. Symbol - c.

DAUGHTER PRODUCT (DECAY PRODUCT)	That nuclide which originates from an isotope by radioactive decay.
DECAY	Of a radioactive substance; the gradual decrease of its activity; its transformation into its daughter product(s). Of a phosphor: the gradual decline of brightness after excitation.
DECAY CURVE	The activity of a radioactive specimen or substance plotted versus time.
DECAY-LAW OF A RADIOACTIVE NUCLIDE	The law which states that the number of atoms decaying in unit time is proportional to the number present.
DECAY PRODUCT	Same as DAUGHTER PRODUCT.
DECONTAMINATION	The removal of unwanted radioactive material from a structure, area, object or person.
DEEP SUB-SURFACE BURST (DEEP UNDERGROUND BURST)	See under CATEGORIES OF BURST.
DEGRADATION	Loss of energy by particles or photons as the result of collision. For neutrons, this is usually called MODERATION.
DELAYED NEUTRONS	Those neutrons which are emitted with a measurable delay following fission.
DELTA RAY	An electron knocked out of an atom by the passage of a fast ionising particle and possessing enough energy to make a number of ions.
DEPTH DOSE	The dose of radiation delivered at a particular depth beneath the surface of a body or other irradiated material (see PERCENTAGE DEPTH DOSE).
DEUTERIUM	Isotope of hydrogen having the MASS NUMBER 2.
DEUTERON	A nucleus of deuterium.
DIFFRACTION	The spreading of waves (e.g. acoustical, optical, radio) around the edges of objects. In connection with a blast wave impinging on a structure, diffraction refers to the passage around and the envelopment of the structure by the blast wave.
DISINTEGRATION	Any process in which a nucleus sends out one or more particles (including photons) either spontaneously or on being hit.

DISINTEGRATION CONSTANT (λ)	The probability per unit time of the decay of a nucleus in a given radioactive nuclide. It determines the exponential decrease with time t of the activity $a = a_o e^{-\lambda t}$; λ is the reciprocal of the MEAN LIFE.
DOSE (RADIOLOGICAL)	A total (or accumulated) quantity of ionising (or nuclear) radiation. The term 'Dose' is often used in the sense of the Exposure Dose, expressed in roentgens, which is a measure of the total amount of ionisation that the quantity of radiation could produce in air. This should be distinguished from the Absorbed Dose given in reps or rads, which represents the energy absorbed from the radiation per gram of specified body tissue. The Biological Dose in rems is a measure of the biological effectiveness of the radiation exposure, and it includes the r.b.e. factor.
DOSE, ABSORBED	Of any ionising radiation, the energy imparted to matter by ionising particles per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the rad. 1 rad = 100 ergs per gramme.
DOSE-RATE (RADIOLOGICAL)	The amount of ionising (or nuclear) radiation to which an individual would be exposed per unit of time. It is usually expressed as roentgens per hour or in multiples or sub-multiples of these units, such as milliroentgens per hour. The dose rate is commonly used to indicate the level of radioactivity in a contaminated area.
DOSE METER (DOSIMETER)	An instrument for measuring dose.
DRAG LOADING (AIR BLAST)	The force on an object or structure due to the transient winds accompanying the passage of the blast wave. The drag pressure is the product of the dynamic pressure and a coefficient which is dependent upon the shape (or geometry) of the structure or object.
DYNAMIC OVER-PRESSURE	The dynamic over-pressure at a point is the product of half the local density of the air and the square of the local particle (or wind) velocity.
DYNE	The unit of force in the c.g.s. system of units. A force of one dyne acting on a mass of 1 gm. imparts to it an acceleration of 1 cm. per sec^2. Approximately 981 dynes are equivalent to 1 gm. weight.

EFFECTIVE ATOMIC NUMBER	For a material containing two or more elements, the number which replaces the Atomic Number in the calculation of the interaction of that material with a given radiation.
EFFECTIVE ENERGY	Of heterogeneous radiation. The quantum energy of that beam of homogeneous radiation which under the same specified conditions is absorbed or scattered to the same extent as the given beam of heterogeneous radiation.
EFFECTIVE HALF-LIFE	The time required for the amount of a particular specimen of radioactive nuclide in the body or in a specified tissue to be reduced to half of its initial value, as a consequence of both biological removal and radioactive decay. The definition can also be applied to non-biological systems.
ELASTIC COLLISION	One in which the incoming particle is scattered without exciting or breaking up the struck nucleus or particle.
ELASTIC SCATTERING	1. Scattering due to elastic collisions. 2. Scattering of a slow neutron by a crystal when the scattered neutron retains its energy, no vibrations being excited in the crystal.
ELECTRON	The negatively charged particle (charge $e = -1.60 \times 10^{-19}$C, mass $m = 9.11 \times 10^{-28}$g) which forms a common constituent of all atoms, its positively charged counterpart of equal mass and opposite charge being called the Positon. However, the word electron is often used to include both negative electrons (Negatons, Negatrons) and positive electrons (Positons, Positrons).
ELECTRON ATTACHMENT (ELECTRON CAPTURE)	The formation of a negative ion when a free electron becomes attached to an atom or molecule.
ELECTRON CAPTURE	1. A radioactive transformation whereby a nucleus captures one of its orbital electrons. Usually the K-electron is captured (K-Capture); but L-Capture may predominate if very little energy is available. 2. See ELECTRON ATTACHMENT.
ELECTRON VOLT	A unit of energy (symbol: eV); the kinetic energy acquired by an electron or other particle of single charge when accelerated through a potential difference of one volt. (1 eV = 1.60×10^{-12} erg). 1,000 eV = 1 keV. 10^6eV = 1 Mev. 10^9eV = 1 Gev (Bev).
ELEMENT	Matter consisting of atoms having the same atomic number.

ELEMENTARY PARTICLE (or FUNDAMENTAL PARTICLE)	Those particles which are held to be simple. They are either stable (electron, positron, proton, photon, neutrino) or disintegrate spontaneously (e.g. neutron, meson, hyperon) into two or more particles liberating an energy which is not small compared to the rest energy of the lightest of them.
END PRODUCT	Of a radioactive series, the stable nuclide that is its final member.
ENERGY (of radiation or of a source of radiation)	The energy of the individual particles or photons of which the radiation consists.
EPICADMIUM NEUTRONS	Neutrons having energies just above the limit (0.5 eV) below which they are absorbed by cadmium.
EPILATION	Falling-out of hair. Removal of the hair with the roots.
EPITHERMAL	Having energy just above the energy of thermal agitation and comparable with chemical bond energies.
ERG	The unit of work or energy in the c.g.s. system of units; equal in magnitude to the work done when the point of operation of a force of 1 dyne is allowed to move 1 cm. in the direction of the force.
ERYTHEMA	A superficial reddening of the skin.
eV	See ELECTRON VOLT.
FALLOUT	The process of the fall-back to the earth's surface of particles contaminated with radioactive material from the atomic cloud. The term is also applied in a collective sense to the radioactively contaminated particulate matter itself.
FAMILY, RADIOACTIVE (RADIOACTIVE SERIES)	A number of radioactive nuclides, each except the first being the daughter product of the previous one; the final member, the end product, although stable is included in the family.
FAST FISSION	Fission induced by 'fast' neutrons having an energy above the fission threshold in 238U, i.e. 1.2 MeV.
FAST NEUTRONS	Neutrons having a kinetic energy higher than some ill-defined limit, usually assumed to be about 0.1 MeV (but see FAST FISSION).

FILM BADGE	A photographic film used as a radiation monitor. It is often partially shielded to differentiate between types and qualities of ionising radiations.
FIRE STORM	A stationary mass fire, generally in built-up urban areas, generating by convection an up-draft with strong in-rushing winds, which keep the fires from spreading while adding fresh oxygen to increase their intensity.
FISSILE	Capable of undergoing fission; sometimes used to mean capable of undergoing fission upon impact of a slow neutron.
FISSION, NUCLEAR FISSION	A nuclear reaction in which a heavy nucleus splits into two fission fragments of comparable masses. The very rare cases of break-up into three (or four) parts of comparable mass are called Ternary (or Quaternary) Fission. Fission can be spontaneous, or it can be caused by the impact of a neutron, a fast charged particle or a photon (Photo Fission). The most important fissile materials are uranium-235 and plutonium-239.
FISSION COUNTER	A counter lined with fissile material or filled with a fissile gas which detects neutrons by the ionisation produced by fission fragments.
FISSION FRAGMENTS	Fission products considered as fast moving particles at their formation.
FISSION PRODUCTS	The stable and unstable nuclides resulting from fission. A distinction should be made between these and the direct fission products or fission fragments which are formed by the actual splitting of the heavy-element nuclei. Something like 80 different fission fragments result from roughly 40 different modes of fission of a given nuclear species, e.g. uranium-235 or plutonium-239. The fission fragments, being radioactive, immediately begin to decay forming additional products, with the result that the complex mixture of fission products so formed contains about 200 different isotopes of over 30 elements.
FISSION SPECTRUM	Of a fissile material: the energy distribution of the neutrons produced by its fission.
FISSIONABLE	Term used in U.S.A. for Fissile.
FLASH BURN	A burn caused by excessive but brief exposure to thermal radiation.
FLUX	The product of the number of particles or photons per unit volume and their average speed.
FREE AIR BURST	See under Categories of Burst.

FREE AIR OVERPRESSURE	The pressure, in excess of the ambient atmospheric pressure, created in air remote from any reflecting surface, by the blast wave from an explosion.
FUSION (NUCLEAR)	Processes whereby the nuclei of light elements, especially those of the isotopes of hydrogen, combine to form nuclei of heavier elements, with the release of substantial amounts of energy.
GAMMA (γ)	Pertaining to gamma radiation (e.g. γ-quantum, γ-absorption, γ-scattering, γ-spectrum, γ-source).
GAMMA RADIATION	Electromagnetic radiation emitted by atomic nuclei.
GAMMA RAYS	Electromagnetic radiations of high quantum energy such as are associated with the acceleration of charged particles and thus accompanying many nuclear reactions, e.g. fission, radioactivity, and neutron capture. Physically, gamma rays are identical with X-Rays of high energy.
GAMMA RAY SPECTROMETER	An instrument for determining the energy distribution of gamma rays.
GEIGER-MÜLLER COUNTER (G-M TUBE, GEIGER COUNTER)	A gas-filled counter operated under such conditions that the magnitude of each pulse is independent of the number of ions initiating it.
GENERATION TIME	The average time required for a neutron born in a fission process to produce a fission itself.
GEOMETRY (Good and Bad)	Good. A situation where the attenuation can be expressed in terms of a simple exponential law. Commonly associated with rectilinear propagation. Bad. A situation where the attenuation is seriously modified by scattering or degradation. Commonly associated with diffuse propagation.
GEOMETRY FACTOR (RADIATION)	The average solid angle at the source subtended by the aperture or sensitive volume of the detector, divided by the complete solid angle (4π).
GeV (or BeV)	Giga-electron-volt = 10^9 electron volts.
GRAMME-RAD	The unit of integral absorbed dose, the absorption of 100 ergs of energy in a given irradiated material or part of that material.

GROUND BURST — See under CATEGORIES OF BURST.

GROUND ZERO — The point on the surface of land or water vertically below or above the point of burst of a nuclear weapon; frequently abbreviated to G.Z.

HALF-LIFE (HALF VALUE PERIOD) — The time in which the amount of a radioactive nuclide decays to half its initial value. Symbols: T, $T_{\frac{1}{2}}$ and $\tau_{\frac{1}{2}}$.

HALF-THICKNESS, HALF-VALUE THICKNESS (HALF-VALUE LAYER abbreviated h.v.l.) — The thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the observed effect to one half. It may be used as an indication of the quality of the radiation or of the opacity of the substance.

HARD (RADIATION) — Referring to radiation; synonymous with penetrating.

HEALTH PHYSICS — The branch of physics dealing with protection against radiation.

HEAVY HYDROGEN — Deuterium. Mass Number 2. Symbol: D.

HEAVY WATER — A synonym for deuterium oxide. D_2O.

HEIGHT OF BURST — The height above the earth's surface at which a bomb is detonated in the air. The optimum height of burst for a particular target (or area) is that at which it is estimated a weapon of a specified energy yield will produce a certain effect over the maximum possible area.

"HOT" — Highly radioactive (but see also HOT ATOM).

"HOT" ATOM — An atom which has an excited energy state or kinetic energy above the thermal level of its surroundings, usually as a result of nuclear processes.

HOT SPOT — Region in a contaminated area in which the level of radioactive contamination is considerably greater than in neighbouring regions in the area.

IMPLOSION	See WEAPON, IMPLOSION TYPE.
IMPULSE, STATIC and DYNAMIC	The integral of the static overpressure (or dynamic overpressure as the case may be) from the blast wave of an explosion and the time during which it acts at a given point, the integration being between the time of arrival of the blast wave and that at which the over-pressure (or dynamic pressure) returns to zero at the given point.
INCOHERENT	Describing a scattered wave; possessing random phase relation with the incoming wave; or, describing wave trains emitted by two or more centres (nuclei, electrons), possessing random phase relation with one another.
INDUCED RADIOACTIVITY	Radioactivity resulting from irradiation of atomic nuclei. Particularly notable in the case of neutron capture by sodium, manganese, silicon or aluminium.
INFRA RED	A portion of the electromagnetic spectrum of which the wavelength is longer than the limit of red vision, approximately 7600 Angstroms (or 0.76 μ) but shorter than radio wavelengths.
INITIAL NUCLEAR RADIATION	Nuclear radiation (essentially neutrons and gamma rays) emitted from the ball of fire and the cloud column, during the first minute after a nuclear explosion.
INTEGRAL ABSORBED DOSE	In a certain region, the energy imparted to matter by ionising particles in that region.
INTENSITY	Of a beam of radiation, the energy flowing per unit time and per unit area perpendicular to the direction of flow.
INTERMEDIATE NEUTRONS	Neutrons having a kinetic energy between that of EPITHERMAL and FAST NEUTRONS.
INTERNAL RADIATION	That radiation reaching a given point in the body or irradiated material which is due directly or indirectly to a source of radiation inside that body or material.
INVERSION (ATMOSPHERIC TEMPERATURE INVERSION)	A region in the atmosphere in which the temperature rises with increasing altitude instead of dropping as it does in the more general case. A particularly stable air layer results.
ION	An atom, or aggregate of atoms, which is not electrically neutral, vis., Positive Ion, Negative Ion. In certain circumstances an electron may be described as a "negative ion".
IONIC YIELD	The number of ion pairs produced per incident particle or quantum.
IONIZATION	Any process by which ions are formed; in particular ionization of a gas by the passage of fast charged particles.

IONIZATION CHAMBER	A gas-filled enclosure containing two or more electrodes, one of which may be its wall. It is used to measure or to detect radiation by means of the ionization current produced therein.
IONIZATION CURRENT	The current due to the movement, in an electric field, of ions and electrons produced by ionizing radiation.
IONIZATION POTENTIAL	The minimum potential difference by which an electron must be accelerated to enable it to ionize a particular atom, molecule or ion.
IONIZING ENERGY	A term sometimes used for the mean energy spent in producing an ion pair in a given material (Symbol: W).
IONIZING EVENT	Any occurrence in which an ion or group of ions is produced; for example, the passage of a charged particle.
IONIZING RADIATION	Electromagnetic or corpuscular radiation capable of producing ions directly or indirectly, in its passage through matter.
IRRADIATION	Exposure to radiation.
ISOBARS (NUCLEAR)	Nuclides having the same mass number but different atomic numbers.
ISODOSE CURVE (ISODOSE CONTOUR)	The curve obtained at the intersection of a particular ISODOSE SURFACE with a given plane.
ISODOSE SURFACE	A surface on which the dose received is everywhere the same.
ISOTONES	Nuclides having the same neutron number but different atomic numbers.
ISOTOPES	Nuclides having the same atomic number but different mass numbers.

kc	kilocurie = 10^3 curie.
kc/s	Kilocycle per second.
keV	Kilo-electron-volt = 10^3 eV.
KILOTON (ENERGY)	The energy of an explosion, expressed in units of 10^{12} calories (or 4.2×10^{19} ergs). This unit is approximately equivalent to the energy produced by the explosion of 1 kiloton (1,000 tons) of T.N.T.

LATENT PERIOD	The period between exposure to radiation and the onset of a particular symptom.
L D 50	See MEDIAN LETHAL DOSE.
LETHAL GUST ENVELOPE	The boundary of the area in any given plane within which the gust-loading effects from a detonation inflict sufficient structural damage to destroy a given aircraft.
LEUCOCYTE	A white blood corpuscle.
LEUCOPENIA (LEUCOCYTOPENIA)	A decrease in the number of leucocytes in the peripheral blood below 5,000 per cubic mm.
LEUKAEMIA	A disease in which there is excessive over-production of white blood cells, and enlargement of the spleen.
LEVEL (NUCLEAR)	One of the energy values at which a given nucleus can exist for an appreciable time (more than 10^{-22} s).
LINE SPECTRUM	An energy distribution of electromagnetic radiation, or of particles, which has sharp maxima (Lines); in contrast to a Continuous Spectrum.
LOADED CONCRETE SHIELD	A concrete shield in which the gravel aggregate is loaded with dense material, to increase absorption of nuclear radiation.
LOW AIRBURST	See under CATEGORIES OF BURST.
MACH NUMBER	Speed in units of the local velocity of sound.
MACH STEM	The shock front formed by the fusion of the incident and reflected shock fronts from an explosion. The term is frequently used with reference to a blast wave, propagated in air, reflected at the surface of the earth. The Mach stem is nearly perpendicular to the reflecting surface and presents a slightly convex (forward) front.
MASS DECREMENT	The number obtained by deducting the mass number of a nuclide from its mass measured on the physical scale of atomic weights. Symbol δ (delta).
MASS DEFECT	The difference between the mass of a nucleus and the sum of the masses of its constituent nucleons.
MASS-ENERGY RELATION (EINSTEIN'S EQUATION)	The formula $E = mc^2$. This relates the change E in the energy of a system with the change m in its mass, and follows from Einstein's Theory of Relativity. (c = velocity of light).
MASS NUMBER	Of a nuclide; the integer A which is nearest to its atomic mass; it is the number of nucleons in the nucleus.

MAXIMUM PERMISSIBLE CONCENTRATION	The recommended upper limit for the concentration of the radioactive substance in any material liable to enter the human body. The value of the limit is dependent among other things on the nature of the radioactive substance and its chemical form.
MAXIMUM PERMISSIBLE DOSE	The recommended upper limit for the dose which may be received during a specified period (usually one week) by a person exposed to ionizing radiation over an indefinite period. So far as is known a normal person so exposed will suffer no harmful effect.
MAXIMUM PERMISSIBLE DOSE RATE	The dose rate which, if constant during a specified period, would give rise to the maximum permissible dose for that period.
MAXIMUM PERMISSIBLE FLUX	That flux of radiation which, if constant during a specified period, would give rise to the maximum permissible dose in that period.
MAXIMUM PERMISSIBLE LEVEL (m.p.l.)	Used to refer loosely to the maximum permissible concentration, dose, dose rate, or flux.
MEAN FREE PATH	The mean distance a particle travels before colliding (Total Mean Free Path) or before something specified happens (e.g. ionization, attachment, etc.).
MEAN LETHAL DOSE	Often used inaccurately for MEDIAN LETHAL DOSE.
MEAN LIFE	Of a radioactive substance, the average time for which its nuclei exist before disintegrating. It is the reciprocal of the DISINTEGRATION CONSTANT and is equal to 1.442 times the HALF-LIFE.
MEAN SURVIVAL TIME	The arithmetic mean of the survival times of individual animals or organisms of a group exposed to a given dose of radiation.
MEDIAN LETHAL DOSE (MLD 50)	That dose of radiation which causes 50 per cent of the individuals in a large group of animals or organisms to die within a specified period. It is commonly, although not universally, accepted at the present time that a gamma dose of about 450 roentgens, received over the whole body in the course of a few hours or less, is the median lethal dose for human beings.
MEGACURIE	A million curies.
MEGATON (ENERGY)	An energy release defined as 10^{15} calories. This is approximately equivalent to that of one million tons of high explosive.
MeV	mega-electron-volt = 10^6 eV.
MICROCURIE	Equal to 10^{-6} curie. (Symbol μc).

MILLICURIE	10^{-3} curie. (Symbol mc).
MODERATION	The slowing down of neutrons on passing through matter, owing to repeated collisions with nuclei.
MODERATOR	Any substance (usually containing light elements) which serves to slow down neutrons without appreciable capture.
MONITOR	A radiation detector designed to meet the special needs of monitoring.
MONITORING	Periodic or continuous determination of the amount of ionizing radiation or radioactive contamination present in a specified region (Area Monitoring), or in or upon a person or his clothing (Personnel Monitoring), or in the air (Air Monitoring), or in water (Water Monitoring). Monitoring may be carried out as a safety measure for purposes of health protection, or to assess and sometimes control the operation of a given machine or process.
MONTE-CARLO METHOD	A method of solving physical problems, e.g. neutron diffusion problems, by a series of repeated statistical experiments performed by applying mathematical operations to random numbers.
MULTIPLE SCATTERING	See SCATTERING.
MULTIPLICATION	The process by which additional neutrons are produced in a critical or subcritical assembly by a chain reaction.

NEAR SURFACE BURST	See under CATEGORIES OF BURST.
NECROSIS	The pathological death of a cell or group of cells in contact with living tissue.
NEGATIVE PHASE (of a blast wave)	That portion of the blast wave in which pressures are below ambient atmospheric.
NEUTRINO	A particle with no charge or rest mass, but spin $\frac{1}{2}$, whose emission in beta processes together with the electron was postulated (Pauli 1930) to save the laws of conservation of energy and angular momentum. There is now good evidence that two kinds exist, each the antiparticle to the other. They are called the neutrino (emitted with positrons) and the antineutrino (emitted with electrons). Both kinds also appear in the decay of some mesons.

NEUTRON — One of the particles of which nuclei consist: of zero charge and slightly heavier (1.00894 amu) than a proton. Free neutrons decay to protons by a beta process, with a half life of about 12 minutes.
Fast neutrons have energies greater than about 0.5 Mev. Slow neutrons are neutrons of low energy. The upper limit of energy is often taken as 1 ev.
Thermal neutrons are in thermal equilibrium with their surroundings. At 15°C. their mean energy is about 0.025 ev.
Epithermal neutrons have energies between those of thermal and fast neutrons.

NEUTRON FLUX — A measure of the number of neutrons crossing unit area in any direction per unit time. It is defined as the product of neutron density and mean velocity.

NEUTRON HARDENING — An increase of the average energy of neutrons diffusing through a medium,caused by the preferential absorption of slower neutrons when cross section decreases with increasing energy.

NOMINAL ATOMIC BOMB — A term used to describe an atomic weapon with a yield of 20 kilotons. (Obsolescent term).

NUCLEAR CHARGE — Of a nuclide, the electric charge carried by each nucleus; measured in elementary charge units it is equal to the atomic number Z (the number of protons in the nucleus).

NUCLEAR ENERGY — Energy released in nuclear reactions, commonly called Atomic energy.

NUCLEAR RADIATION — Particulate and electromagnetic radiation emitted from atomic nuclei in various nuclear processes. The important nuclear radiations from the weapons standpoint are alpha and beta particles, gamma rays and neutrons.

NUCLEAR REACTION — Any nuclear disintegration caused by the impact of a particle or a photon; and resulting in fragments specified as to character and state of excitation.

NUCLEUS (ATOMIC NUCLEUS) — The small central positively charged region of an atom which carries essentially all the mass. Except for the nucleus of ordinary (light) hydrogen, which is a single proton, all atomic nuclei contain both protons and neutrons. The number of protons determines the total positive charge or atomic number; this is the same for all the atomic nuclei of a given chemical element. The total number of neutrons and protons, called the mass number, is closely related to the mass (or weight) of the atom. The nuclei of isotopes of a given element contain the same number of protons but different numbers of neutrons.

NUCLIDE — A species of atom characterised by its mass number, atomic number, and nuclear energy state.

ORBITAL ELECTRON (SHELL ELECTRON)	An electron in the extra-nuclear structure of an atom.
OVER-PRESSURE	The transient pressure, usually expressed in pounds per square inch, exceeding the ambient pressure, as manifested in the shock wave from an explosion. The peak overpressure is the maximum value of the overpressure at a given location and is generally experienced at the instant the shockwave reaches that location.
PAIR PRODUCTION	The formation of an electron and a positron (or generally of a particle and its anti-particle) through the interaction of a photon or a fast particle (usually an electron) with the field of an atomic nucleus or other particle; or through de-excitation of an excited nucleus (Internal Pair Production).
PARTIAL EXPOSURE	Exposure of part of the body to ionizing radiation.
PARTITION OF ENERGY	The distribution between nuclear radiation, thermal radiation and blast, of the total energy released by the detonation of a nuclear weapon. The exact distribution is a function of time and of the weapon yield, and of the medium in which the weapon is detonated.
PEAK DOSE	The dose delivered to an irradiated body or material by external radiation measured at that depth below the surface of the material where the absorbed dose rate is a maximum.
PERCENTAGE DEPTH DOSE	The DEPTH DOSE expressed as a percentage either of the surface dose or, for megavoltage radiation, as a percentage of the peak dose below the surface.
PHOTO DISINTEGRATION	Any nuclear reaction caused by a photon and resulting in the emission of charged fragments or neutrons.
PHOTO EFFECT (NUCLEAR)	The complete absorption of a photon by a nucleus with the emission of one or more nucleons.

PHOTON (LIGHT QUANTUM)	A quantum of electromagnetic radiation, possessing the energy $h\nu$ (h Planck's constant, ν the frequency).
PLASTIC RANGE	The strain range in which a material will not fail when subjected to the action of a force, but will not recover completely, so that a permanent deformation results when the force is removed. Plastic deformation refers to dimensional changes recurring within the plastic range.
POSITIVE PHASE (Air Blast)	That portion of the blast wave in which pressures are above ambient atmospheric.
PRECURSOR	1. Air blast; conditions under which the shock wave is greatly modified from the simple form. 2. Of a nuclide; any radioactive nuclide which precedes it in a decay chain.
PROMPT FISSION NEUTRONS	Those fission neutrons which are emitted in the fission process, or from the freshly formed fission fragments, without measurable delay.
PROMPT GAMMAS OR NEUTRONS	Those gamma rays or neutrons which are emitted as a result of fission and practically at the same time.
PROTON	A nuclear particle of unit mass number having a charge equal and opposite to that of an electron (1.60×10^{-19}C) and having a mass of 1.0079 amu, 1.672×10^{-24} gm. The nucleus of an atom of hydrogen (^{1}H).
Q-VALUE (DISINTEGRATION ENERGY)	For a given nuclear disintegration, the amount of energy released. (A negative Q-VALUE means energy consumed.)
QUANTUM (Plural: QUANTA)	The unit amount of a quantity (e.g. action, angular momentum, or energy of a harmonic oscillator) which, according to the Quantum Theory can change by integral multiples only of that unit amount.

R; r	Symbol for ROENTGEN
RAD	A unit of absorbed radiation dose. It is 100 ergs per gram of the absorbing material or tissue.
RADIAC INSTRUMENTS	A contraction of "radioactivity, detection, identification and computation", used to describe various radiation monitoring and detecting instruments designed for defence.
RADIATION LENGTH	For a given material the path length in which a relativistic electron will, on an average, lose 1/e of its energy by RADIATIVE COLLISIONS. (e = 2.7183 approximately.)
RADIATION SICKNESS	A condition, following irradiation, characterised by early malaise, vomiting and blood changes of varying severity. For further details see Part VII.
RADIOACTIVE CAPTURE	See CAPTURE, RADIATIVE.
RADIATIVE COLLISION	A collision between two charged particles (usually an electron and a nucleus) in which part of the kinetic energy is converted directly into electro-magnetic radiation (BREMSTRAHLUNG).
RADIOACTIVE	Possessing or pertaining to RADIOACTIVITY.
RADIOACTIVE EQUILIBRIUM	Among those successive radioactive products having a shorter life than their common parent, the condition in which the products decay exponentially with the period of the parent. When the life of the parent is very much longer than that of any of the products the equilibrium is called Secular, in which case the number of atoms disintegrated per unit time is the same for all products. Otherwise the equilibrium is referred to as Transient.
RADIOACTIVITY	The property of certain nuclides, or of materials containing such nuclides, of emitting Radiation by the spontaneous disintegration of their nuclei. Natural Radioactivity is due to nuclides that occur in nature. Artificial (deprecated) or INDUCED RADIOACTIVITY is due to nuclides formed under bombardment with particles or photons.
RADIOACTIVITY, INDUCED	Radioactivity produced directly or indirectly by bombardment with particles or photons.
RAIN-OUT	The enhanced rate of deposition of fall-out associated with local rainfall.
RANGE	1. Of ionizing particles of given energy, the distance they travel in a given medium before ceasing to ionize. The medium if not specified, is air at N.T.P. The Mean Range is obtained by averaging the ranges of a large number of individual particles of the same energy; the fluctuation of range among them is called Range Straggling. If the number of particles travelling further than a given distance is plotted as a function of that distance one obtains a curve with a steeply dropping portion near the mean range; straight extrapolation of that portion gives the Extrapolated or Visual Range.

2. Of nuclear force, the distance (of the order of the nuclear radius, i.e. of 10^{-13} cm) over which the force is significant.
EFFECTIVE RANGE is the radius of a **Spherical Well** which possesses the same effect, in first approximation, as the force under study.

R.B.E. (r.b.e.) RELATIVE BIOLOGICAL EFFECTIVENESS	The ratio of the number of rads of gamma or X-radiation of a certain energy which will produce a specified biological effect, to the number of rads of any other energy or type of radiation required to produce the same effect.
RECOMBINATION	The disappearance of positive and negative ions by mutual neutralization.
RECOMBINATION COEFFICIENT	For an ionized material (usually gas) the coefficient A in the expression An_+n_- for the rate at which pairs of positive and negative ions, present at densities n_+ and n_- respectively, neutralise each other.
REFLECTED PRESSURE	The total pressure which results instantaneously at the surface when a shock or blast wave travelling in one medium strikes another medium, e.g. at the instant when the front of a blast wave in air strikes the surface of an object or structure.
R.E.M. (rem) (ROENTGEN EQUIVALENT MAN/MAMMAL)	A unit of biological dose of radiation derived from the term Roentgen equivalent man/mammal. It is the absorbed dose of any ionizing radiation which has the same biological effectiveness as 1 rad of X-radiation with average specific ionization of 100 ion pairs per micron of water, in terms of its air equivalent, in the same region. The number of rems of radiation is equal to the number of rads absorbed multiplied by the RBE of the given radiation (for a specified effect).
R.E.P. (rep) (ROENTGEN EQUIVALENT PHYSICAL)	The dose of radiation which, when delivered to a given mass of soft tissue, produces the same real energy conversion as 1 roentgen delivered to the same mass of air (approximately 84 ergs per gram, but figures between 60 and 100 are quoted). This unit may be used for radiations other than X- or gamma radiation and for X- or gamma radiation when electronic equilibrium has not been achieved.
RESIDUAL RADIATION	Nuclear radiation, chiefly beta particles and gamma rays, which persists for some time following a nuclear explosion. The radiation is emitted mainly by the fission products and other bomb residues in the fallout, and to some extent by earth and water constituents and other materials in which radioactivity has been induced by the capture of neutrons.

ROENTGEN (r) A unit of dose defined internationally as the quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign. Note that 0.001293 gram is the mass of 1 cc. of dry atmospheric air at 0°C and 760 mm of mercury pressure. (Symbol: r.).

ROENTGEN RAYS Same as X-rays, discovered by Professor W. C. Roentgen in 1895.

RUTHERFORD SCATTERING See COULOMB SCATTERING.

SCATTERING 1. The broadening of a collimated beam of Radiation on passing through matter.

2. The deflection suffered by individual photons or particles on interacting with the nuclei, electrons (or conceivably photons) in the material (or radiation field) through which they pass. Single Scattering is the result essentially of a single interaction; Plural Scattering, of a few; Multiple Scattering, of many. In the case of charged particles Multiple Scattering refers to the cumulative effect of many interactions, each causing very little deflection. In Inelastic Scattering the scattered particle or photon loses energy by exciting the struck nucleus or - in the scattering of slow neutrons - the crystal lattice of the scatterer, whereas in Elastic Scattering that kind of energy loss is absent. Scattering can be considered as a wave phenomenon and is often characterised by the Scattering Amplitude or Scattering Length a, where na^2 equals the Electric Scattering Cross-Section; the sign of "a" is of importance for interference phenomena and for the refractive index of the scatterer.

SECONDARY ELECTRON An electron ejected from a free atom or molecule or from the surface of a body as a result of the impact of a charged particle or photon.

SECONDARY IONIZATION Ionization produced by secondary radiation.

SECONDARY RADIATION Particles or photons produced by the inter-action with matter of a radiation regarded as primary.

SHALLOW SUB-SURFACE BURST See under CATEGORIES OF BURST.

SHIELDING Material of suitable thickness and physical characteristics used to protect personnel from radiation during manufacture, handling and transportation of fissile and radioactive materials.

SHIELD — An obstruction which tends to protect personnel or materials from the effects of a nuclear explosion.

SHOCK FRONT — The fairly sharp boundary between the pressure disturbance created by an explosion (in air, water, or earth) and the ambient atmosphere, water, or earth, respectively. It constitutes the front of the shock or blast wave.

SKIN DOSE — The quantity of radiation actually absorbed in the skin.

SKY-SHINE — See AIR SCATTER.

SLOW NEUTRONS — Neutrons having kinetic energies of not more than a few electron ~~bolts~~ volts. Sometimes loosely used to mean thermal neutrons.

SLUGS — Mass in pounds divided by 32.2.

SOFT RADIATION — Radiation with low penetrating power.

SPECIFIC ACTIVITY — The activity per unit mass of an element containing a radioactive nuclide. The term may also be used for the activity per unit mass of any material in which the element occurs, or of the pure radioactive nuclide.

SPECIFIC IONIZATION — The number of ion pairs formed by an ionizing particle per unit length of its path.

SPECTRUM — A visual display, a photographic record or plot of the distribution of radiation of a given kind as a function of its wavelength, energy, momentum, mass, or any other related quantity. Sometimes used to describe the distribution itself.

SUBCRITICAL — Having an effective Multiplication Constant less than unity, so that the nuclear chain reaction is not self-sustaining.

SUPERCRITICAL — Having an effective Multiplication Constant greater than one, so that the nuclear chain reaction is not merely self-sustaining but increases.

SURFACE BURST — See under CATEGORIES OF BURST.

SZILARD CHALMERS PROCESS — A chemical change caused by a nuclear transformation in which there is no change in atomic number.
The term is most commonly used for reactions in which the atoms are made radioactive by the transformation and fail to exchange completely with the parent material. Radioactive elements of high specific activity can be obtained by this means.

TENTH VALUE THICKNESS	The thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces its effect to one tenth.
TERNARY FISSION	The (very rare) break-up of a heavy nucleus into three fragments of comparable mass; also used for the less rare break-up into three charged fragments, one of which (e.g. an alpha particle) is much lighter than the others.
THERMAL COLUMN	A large block of moderating material extending away from the core of a reactor to provide at its other end, for experimental purposes, a flux of almost pure thermal neutrons.
THERMAL CROSS-SECTION	The cross-section for any process as measured with thermal neutrons.
THERMALIZE	To bring neutrons into thermal equilibrium with their surroundings.
THERMAL NEUTRONS	Neutrons in thermal equilibrium with their surroundings. At 15°C the most probable velocity is 2,200 metres per second, corresponding to a kinetic energy of 0.025 eV.
THERMAL RADIATION	Electromagnetic radiation emitted from the ball of fire as a consequence of its very high temperature; it consists of ultra-violet, visible, and infra-red radiations.
THERMAL YIELD	That part of the total yield of a nuclear weapon which is radiated as thermal energy.
THERMONUCLEAR REACTION	A reaction in which very high temperatures are used to assist fusion of nuclei of light elements, thereby releasing fussion energy.
THERMONUCLEAR WEAPON	A weapon to whose energy release thermonuclear reactions contribute.
THOMSON SCATTERING	The scattering of photons by a free charged particle (in particular by an electron) according to J. J. Thomson's classical formula, which is valid provided the photon energy is much less than the rest energy of the particle.
THRESHOLD DOSE	The smallest dose of radiation that will produce cumulative results.
T.N.T. EQUIVALENT	A measure of the energy released in the detonation of a nuclear weapon, or in the explosion of a given quantity of fissile material, expressed in terms of the quentity of T.N.T. which would release the same amount of energy when exploded. The T.N.T. equivalent is usually stated in kilotons or megatons. The basis of the T.N.T. equivalence is that the explosion of 1 ton of T.N.T. releases 10^9 calories of energy. See also KILOTON.
"TOLERANCE DOSE"	See MAXIMUM PERMISSIBLE DOSE.

TRACE	A small quantity of material measurable only by special techniques.
TRACER (ISOTOPIC TRACER)	A substance, recognizable by its radioactivity or unusual isotopic composition, which is introduced into a system (physical, chemical or biological) in order to trace the behaviour of some component of that system.
TRACK	Of an ionizing particle. Its path as revealed, for example, in a cloud chamber or photographic emulsion.
TRIPLE POINT	The intersection of the incident, reflected, and fused (or Mach) shock fronts accompanying an air burst. The height of the triple point above the surface, i.e. the height of the Mach stem, increases with increasing distance from a given explosion.
TRITIUM	The isotope of hydrogen having a mass number of 3.
TROPOPAUSE	The boundary between the troposphere and the stratosphere.
TROPOSPHERE	The lower portion of the earths atmosphere, extending up to some 22,000 - 40,000 feet, characterised by a general decrease of temperature with height, and within which most of the phenomena commonly associated with "weather" are found to occur.
ULTRA-VIOLET	A portion of the electromagnetic spectrum beyond the violet end of the visible spectrum, in which the wavelengths are shorter than 4,000 Ångstroms (A.U.) but longer than X- ray wavelengths.
W-CURVE	The curve, shaped somewhat like an inverted letter W, depicting the relation between relative abundance of fission products and their atomic number.

WEAPON, GUN TYPE	A nuclear weapon in which the assembly of sub-critical masses of fissile material produces a super-critical mass, resulting in an atomic explosion.
WEAPON, IMPLOSION TYPE	The type of nuclear weapon in which a sub-critical configuration of fissile material is compressed into a super-critical state by a centrally directed radial shock, to produce an atomic explosion.
WILSON CLOUD	See CONDENSATION CLOUD.
WINDOW (of a counter)	That portion of the wall of a counter which is made thin enough for radiation of low penetrating power to enter.
YIELD (RADIOCHEMICAL YIELD)	The total effective energy released in a nuclear explosion. It is usually expressed in terms of the equivalent tonnage of T.N.T. required to produce the same energy release in an explosion. The total energy yield is manifested as nuclear radiation, thermal radiation, and shock (and blast) energy, the actual distribution being dependent upon the medium in which the explosion occurs (primarily) and also upon the type of weapon and the time after detonation. Symbol W.
Z	Symbol for ATOMIC NUMBER.

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(1) Effects of Nuclear Weapons, U.S.A.E.C., 1957.

(2) A Glossary of Terms in Nuclear Science and Technology, American Society of Mechanical Engineers, 1955.

(3) British Standard 2597 : 1955. Glossary of Terms used in Radiology.

(4) Chambers Technical Dictionary, (1953).

(5) Draft British Standard. Glossary of Terms used in Nuclear Science. CX(USM)8230, September, 1957.

PART III - DAMAGE BY AIR BLAST

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PART III - AIR BLAST DAMAGE

Symbols and Units

p = Pressure in general (pounds per square inch)

P = Ambient static pressure of undisturbed atmosphere (p.s.i.)

p_s = Static overpressure (p.s.i.)

P_s = Peak static overpressure (p.s.i.)

p_d = Dynamic overpressure (p.s.i.)

P_d = Peak dynamic overpressure (p.s.i.)

P_{sg} = Peak stagnation overpressure (p.s.i.)

p_r = Reflection overpressure (p.s.i.)

P_r = Peak reflection overpressure (p.s.i.)

I = Total impulse imparted to target.

ρ = Density in general (Slugs per cubic foot)

ρ_o = Density of air under standard conditions.
(0.0024 Slugs / cu.ft. at 15°C and 760 mm.)

Slugs = Mass in pounds divided by 32.2

u = Air particle velocity (ft / sec)

U = Shock front velocity (ft / sec)

τ_o = Duration of positive phase of blast wave (secs)

α = Reciprocal of τ_o (secs.$^{-1}$)

t = Time after arrival of the shock front at the point considered (secs)

t_o = Time of arrival of the shock front at the point considered (secs)

1 KT = 10^{12} calories total energy release
$\approx 0.45 \times 10^{12}$ calories blast energy at sea level
$\approx$ Blast effects of 450 short tons of T.N.T.

W = Total energy release in an explosion (kilotons),
For definitions of s, g, t_1 see section 2.2.1.

PART III - AIR BLAST DAMAGE

CHAPTER 1 - INTRODUCTION

1.1. The nature of Air Blast

The formation and propagation of the air blast wave from a nuclear explosion and its interaction with the ground are described in the British Manual on the Effects of Atomic Weapons (Chapter 1)†, but a brief resumé will be given here. In free air there expands radially from the explosion a shock front, in which the pressure rises abruptly; this is followed first by a region in which the pressure decreases to atmospheric (the positive phase), and then by a region in which the pressure falls below atmospheric before finally returning to atmospheric (the negative phase). In the positive phase a powerful wind blows away from the explosion, and towards the explosion during the negative phase. Both the pressure excursion and the wind velocity are much less intense in the negative phase than in the positive phase, and normally only the positive phase is of importance in considering target response to nuclear explosions. (M.E.A.W., 1.2).

When the shock front from an air burst reaches the ground it is reflected back into the air; the flow behind the reflected shock is parallel to the ground and the static pressure is increased. So-called regular reflection continues out to a point on the ground where the angle of incidence of the original shock front with the ground is about 40°. The point of intersection of the incident and reflected shocks, the triple point, then begins to rise above the ground and there is formed a so-called Mach stem which meets the ground at 90°. (M.E.A.W. 1.5.). The result is that isolated ground targets more distant than about 0.85/1.5 times the height of the burst are struck by the single combined blast wave moving parallel to the ground. This situation will be assumed, unless otherwise stated, in the analysis of blast loading of ground structures given in this chapter. The more complex case of multiple incident shocks, such as may be experienced at points closer to ground zero, or above the surface, or wherever the blast is reflected from neighbouring objects, can be derived from the single shock case when required. The reader is reminded that blast pressures are not simply additive except for the weakest shocks, and is referred to any Aerodynamic textbook or to R.H. Cole (see Reference 6) for the appropriate treatment. Practical cases may necessitate experimental investigation at model scale, or in some instances at full scale.

The peak overpressure immediately above the surface is a somewhat complex function of the relative position of weapon and target, with respect to the surface of the earth, and also of weapon yield. It is therefore customary to present the data in the form of "height of burst" curves for various surfaces, with a bomb total yield of 1 KT, and to scale all the distances with $W^{\frac{1}{3}}$ for other sizes of burst. These data are given for various conditions in M.E.A.W. Section 1.6 and Figures 1.6.1 and 1.6.2. For ease of reference peak air overpressure curves for "average" surface conditions are given in Figure 1, and for sub-surface bursts in Chapter 9, section 9.4.1. Fig.1. Similarly, curves for the duration of the positive phase are given in Figure 2. Fuller details are given in M.E.A.W. Section 1.8.

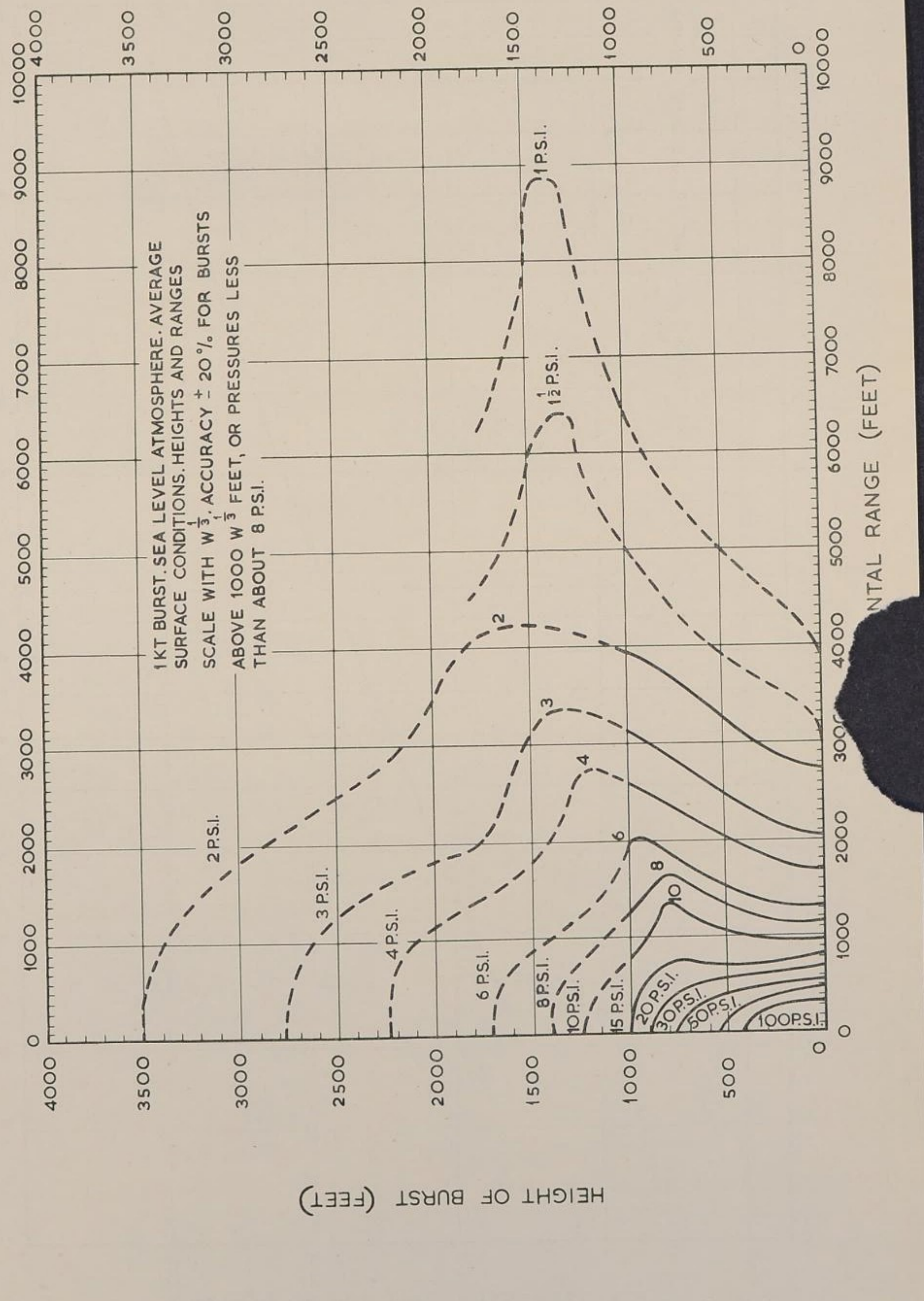
† Reference (1)

The winds associated with these blast waves give rise to drag forces which are expressed in terms of the so-called Dynamic over-pressure. This is discussed in M.E.A.W. 1.2.B. and defined and quantified in Section 1.3 and Figure 4 below.

References

(1) Manual on the effects of Atomic Weapons. Published by the Atomic Weapons Research Establishment, Aldermaston 1955.

(Secret/Atomic/U.K. Eyes only)



PEAK AIR OVERPRESSURE JUST ABOVE THE SURFACE

PART III
CHAPTER 1
SECTION 1.1.
FIGURE 2

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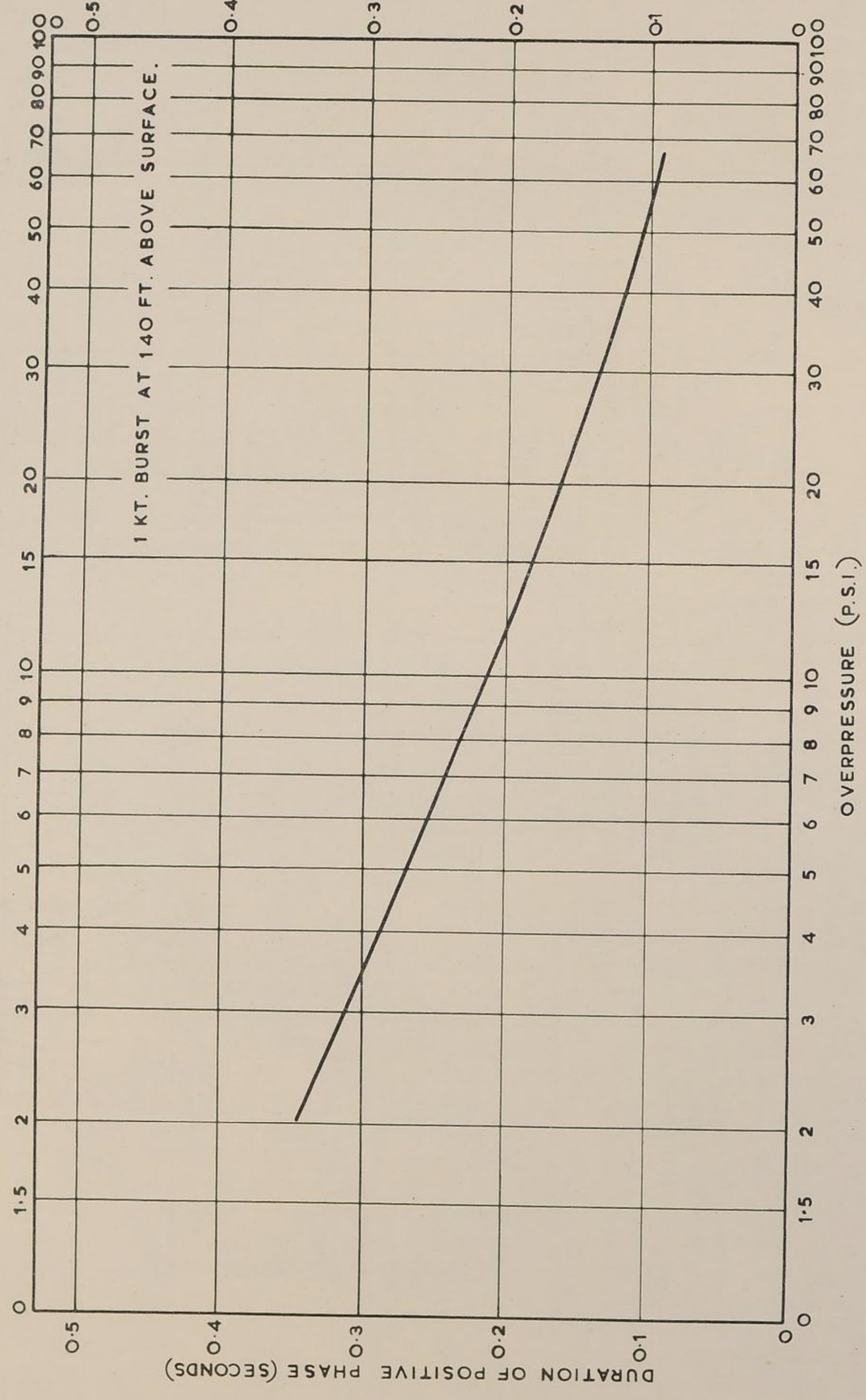
D.N.W.
SEPT. 1957



DURATION OF POSITIVE PHASE OF AIR BLAST VERSUS OVERPRESSURE

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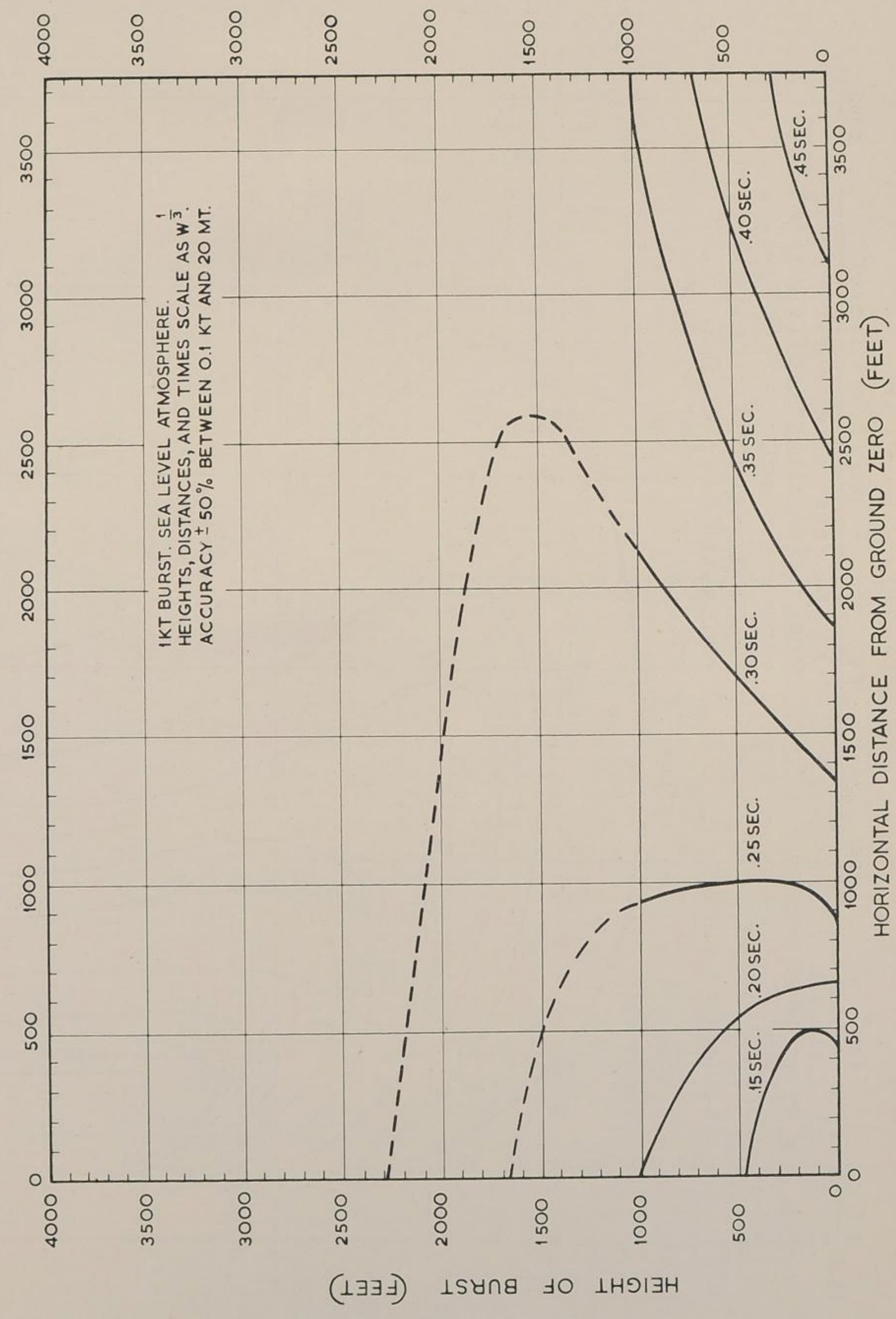
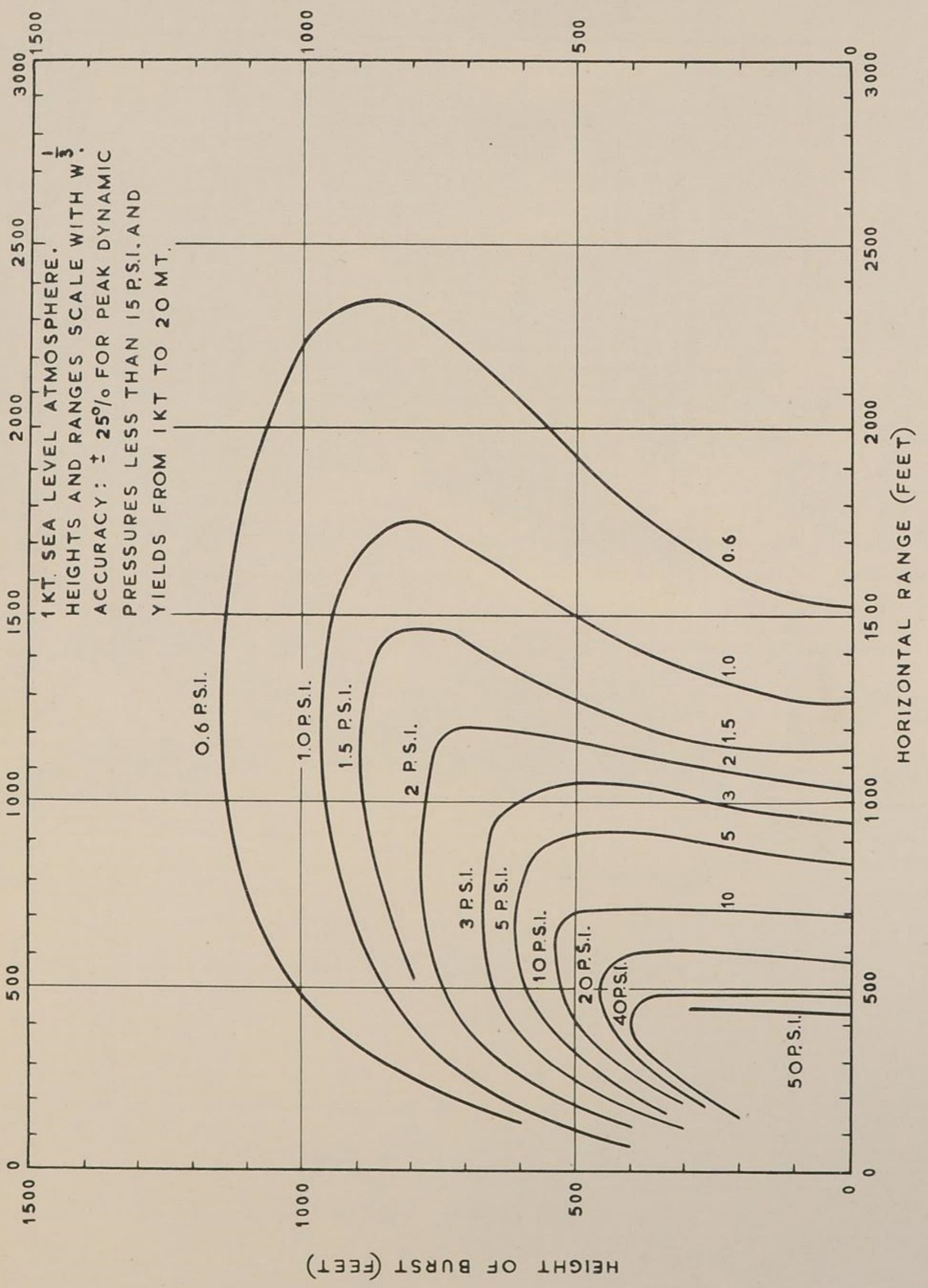


DURATION OF POSITIVE PHASE OF AIR BLAST
AT SCALED DISTANCES AND HEIGHTS OF BURST.



PEAK AIR DYNAMIC OVERPRESSURES
JUST ABOVE THE SURFACE

1.2. Propagation of Air Blast

Over certain types of terrain bursts within certain yield values dependent upon burst height give a special type of air blast known as the "Precursor Effect". When this occurs the usual single shock wave is replaced by a double shock system. This system consists of a relatively weak shock followed by a region of irregular but roughly constant pressure, and then a second stronger shock followed by the normal type of decreasing wave, and is accompanied by great turbulence. The phenomenon arises because a surface layer of ground and air is heated by thermal radiation from the explosion before the arrival of the blast wave, and the latter is then propagated more rapidly in the heated layer than in the air above. Over friable soil this upward flow of air may scoop up soil and produce a violent sand storm which can be very damaging to targets in its path. It is not thought that this effect would occur over water or wet soils but the liklihood of its occurrence over built-up areas is uncertain. (M.E.A.W.1.5.B).

It is believed that if surface condition requirements are met, a precursor will be formed whenever -

(1) $50\,W^{\frac{1}{3}} <$ height of burst in feet $< 450\,W^{\frac{1}{2}}$

and (2) Arrival time of blast wave at Ground Zero < 0.5 secs.

The overall result is that in such conditions the pressure wave is diverted and reaches less than the peak values it otherwise would at a given distance, whereas the drag forces are greatly increased by the turbulence and sand burden. Significant precursor phenomena have never been observed at greater ranges than the 8 p.s.i. contour.

At longer ranges from the explosion it may be necessary to allow for any special terrain or meteorological conditions (M.E.A.W. 1.7, 1.9, 1.11.7). The effects of wind may be approximated by considering an equivalent burst point displaced by the amount of the wind movement up to the moment of arrival of the blast. Wind velocity gradient effects are considered in Reference (7).

No information is available concerning blast propagation through a built-up area, although it is clear that some additional attenuation must result.

1.3. Blast Parameters

A number of shock wave parameters are used in blast damage calculations. In any detailed analysis of damage, no one of these is sufficient to specify the behaviour of a complex target, though the attempt is often made in more elementary treatments. They are however important elements in more critical treatments such as are described in this section. For convenience, some definitions are now given.

Static Overpressure - The air following the shock is at a higher static pressure than it was before being overtaken by the shock. The excess over the ambient atmospheric pressure (P) is known as the static over-pressure (p_s). It takes its greatest value immediately behind the shock discontinuity: its value there is called the peak over-pressure (P_s). Further behind, its value decays to zero and negative values.

The nearest practical approximation to p_s is the pressure rise at a hole near the centre of a side face of an object extending along a radius from ground zero. P_s is sometimes loosely referred to as the 'side-on' pressure.

Values of the peak static overpressure in the air just above the ground as a function of burst height and distance from ground zero are given in Section 1.1 Figure 1 and in Figures 1.1.1. and 1.6.2. of M.E.A.W. The free air pressure/distance curve is given in M.E.A.W. 1.2.1.

The shape of the decay/time curve for the static overpressure depends on the position of the point of observation relative to the transition to Mach reflection.

At points well into the region of Mach reflection a close fit to the positive phase is given (1) by the formula -

$$p = p_s \quad (1-\alpha t)e^{-0.77\,\alpha\ t p_s^{\frac{1}{4}}} \qquad (1.1)$$

where p_s is expressed in p.s.i.

α is the reciprocal of duration of positive phase (sec^{-1})

t is the time measured from the arrival of the shock front at the point considered (sec.)

For many applications the simpler form due to Friedlander may be used. This is -

$$p = p_s \quad (1 - \alpha t)e^{-\alpha t} \qquad (1.2)$$

Some indication of the shape of the curve in the region of the transition to Mach reflection is given in Figure 1.8.4. of M.E.A.W. and in Reference (2).

Dynamic Overpressure - The air following the shock is moving at a gust velocity u (subsonic or supersonic according to shock strength) which is less than the velocity of the shock front. It is also at a higher density ρ than before the passage of the shock. The significant quantity is the kinetic energy per unit volume of air: this affects the pressure experienced at any

Reflection Pressure - When a shock wave strikes an object, a complex set of phenomena ensues, as outlined in ~~paragraph~~ SECTION 2.1. Among these is head-on reflection from the front face. A very weak shock behaves acoustically, the peak overpressure at the wall being $2P_s$. For moderate and strong shocks, at normal incidence the "reflection pressure" is relatively higher - up to nearly $8P_s$ (see 2.1 and Figures 1 and 2). The reflection coefficient is the ratio of reflection pressure to P_s; it is shown in Figure 2 for values of P_s from 1 to 1000 p.s.i.

References

(1) Ministry of Supply (H.E.R.) - S.F.P. Laboratory Note 1/53 (Secret)

(2) Atomic Weapons Research Establishment - Report No.0-37/55 (Secret/Atomic/Discreet)

(3) Ministry of Supply - A.R.E. Report No. 30/50 (Secret/Discreet)

(4) Atomic Weapons Research Establishment - Report No.E5/55 (Secret/Discreet)

(5) Capabilities of Atomic Weapons. A.F.S.W.P. June, 1955. U.S. Department of the Army Technical Manual TM.23-200 (Secret/Atomic)

(6) Cole, R.H. Underwater Explosions.

(7) A.W.R.E. Report No. 0-2/57 "The effects of Meteorological conditions on the Propagation of Blast waves" (Official use only)

point of an object other than the central region of a side face as described above. We therefore define dynamic over-pressure p_d as - $p_d = \frac{1}{2} \rho u^2$ (1.3)

The value of the dynamic over-pressure immediately behind the shock front is given by -

$$P_d = \frac{2.5\, P_s^{2}}{7P + P_s} \qquad (1.4)$$

where P is the ambient pressure of the undisturbed atmosphere. The drag force per unit area exerted by the wind on an object is the product of p_d and the drag coefficient (C_d) for the object. This drag is due to the obstruction of the air flow by the object, and acts on the projected area normal to the flow. It is not due to skin friction on surfaces parallel to the flow. Values of the average drag coefficient for several simple shapes are given in Section 2.4.

A method of calculating the decay of dynamic overpressure is given in Reference (3), but for most purposes the dynamic pressure can be assumed to vary as $(p_s)^{1.8}$, where p_s is the static overpressure in the blast wave. That is, at time t :-

$$\frac{(p_d)_t}{p_d} = \left[\frac{(p_s)_t}{p_s}\right]^{1.8} \qquad (1.5)$$

American information suggests that under "Precursor" conditions the dynamic over-pressure may be increased by a factor of 20 or more owing to the increased momentum of the grit-laden air.

<u>Stagnation Pressure</u> - At the centre of the front face of an object facing towards ground zero there is a point - the stagnation point - where the flow divides and the incident air stream is brought to rest. The stagnation pressure is the static pressure at this point. It is convenient to define stagnation pressure as the pressure the air stream would assume if brought to rest isentropically. The initial stagnation overpressure is given by -

$$P_{sg} = P{+P}\left[1 + \frac{5P_s^{\,2}}{7(7P + P_s)\,(P + P_s)}\right]^{3.5} - P \qquad (1.6)$$

At great enough distances from the burst, where P_s has become small in relation to P, so that compressibility effects can be neglected (corresponding to gust velocities under about 300 m.p.h.), the stagnation over-pressure approximates to p_d, the dynamic overpressure, PLUS P_s

The practical measure of the stagnation pressure is the pressure developed in an ideal pitot tube facing towards the explosion, after the incident shock has passed away and a quasi-steady state exists. As only the peak value is normally of interest, it is written in this manual as P_{sg}.

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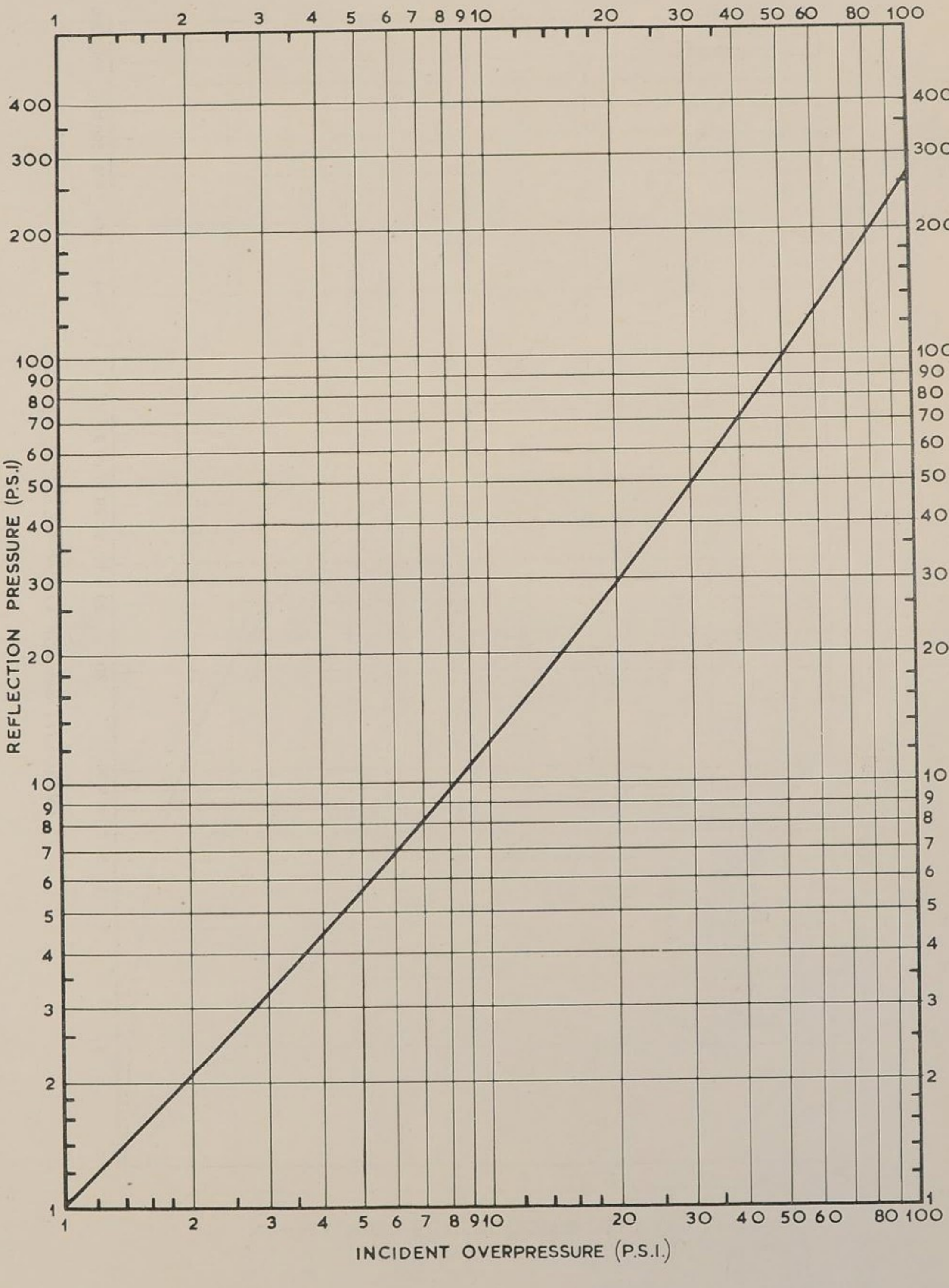

REFLECTION (PEAK ~~INITIAL~~ STAGNATION) PRESSURE AS A FUNCTION OF SHOCK OVERPRESSURE

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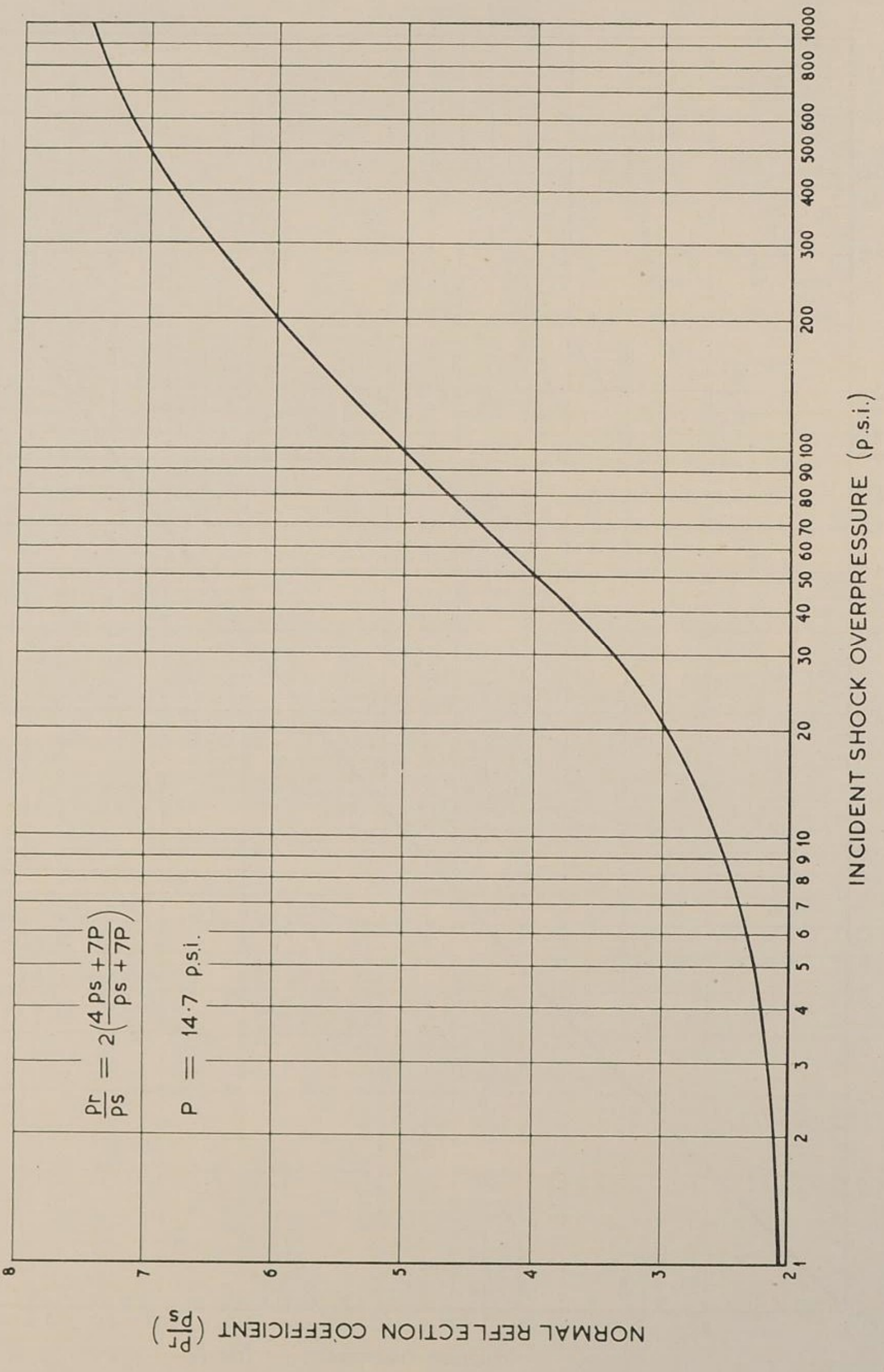


NORMAL REFLECTION COEFFICIENT
AS A FUNCTION OF SHOCK OVERPRESSURE

CHAPTER 2. THE EXTERNAL BLAST LOADING OF STRUCTURES

2.1. General sequence of events

Throughout this section it will be assumed that the target is within the region of Mach reflection, so that the blast wave consists of a single shock rise followed by a region of steadily decreasing pressure. The subsequent negative phase can generally be neglected. At distances from the explosion which we consider, the shock front may be considered to be plane and vertical. At high blast pressures the appearance of locally supersonic flow modifies the following analysis, which is therefore limited to incident blast over-pressures of about 30 p.s.i.

The sequence of events when the blast wave hits an idealised rectangular target face-on may be seen from Figures 1 and 2. The incident shock is reflected from the front face leaving a region of still air at the normal or head-on reflection over-pressure (P_r). Values of P_r derived from the equation

$$P_r = 2 P_s \frac{4 P_s + 7P}{P_s + 7P} \qquad (2.1)$$

are given in figure ~~1.4.~~ 2 OF SECTION 1.3

This air then flows round the edges of the building causing rarefaction waves to travel across the region between the front wall and the reflected shock, weakening the latter. The reflected shock joins the incident shock a short distance from the surface of the building, and a weak Mach stem is produced which is slightly stronger (approximately 10%) than the incident shock. The flow of air round the edges of the front wall produces a vortex loop over the roof and side walls, as shown in Figure 1. This vortex, because of its finite curvature, separates from the building near the junction of the roof with the side walls. The vortex is a region of high rotational velocity and low pressure which then travels relatively slowly over the target.

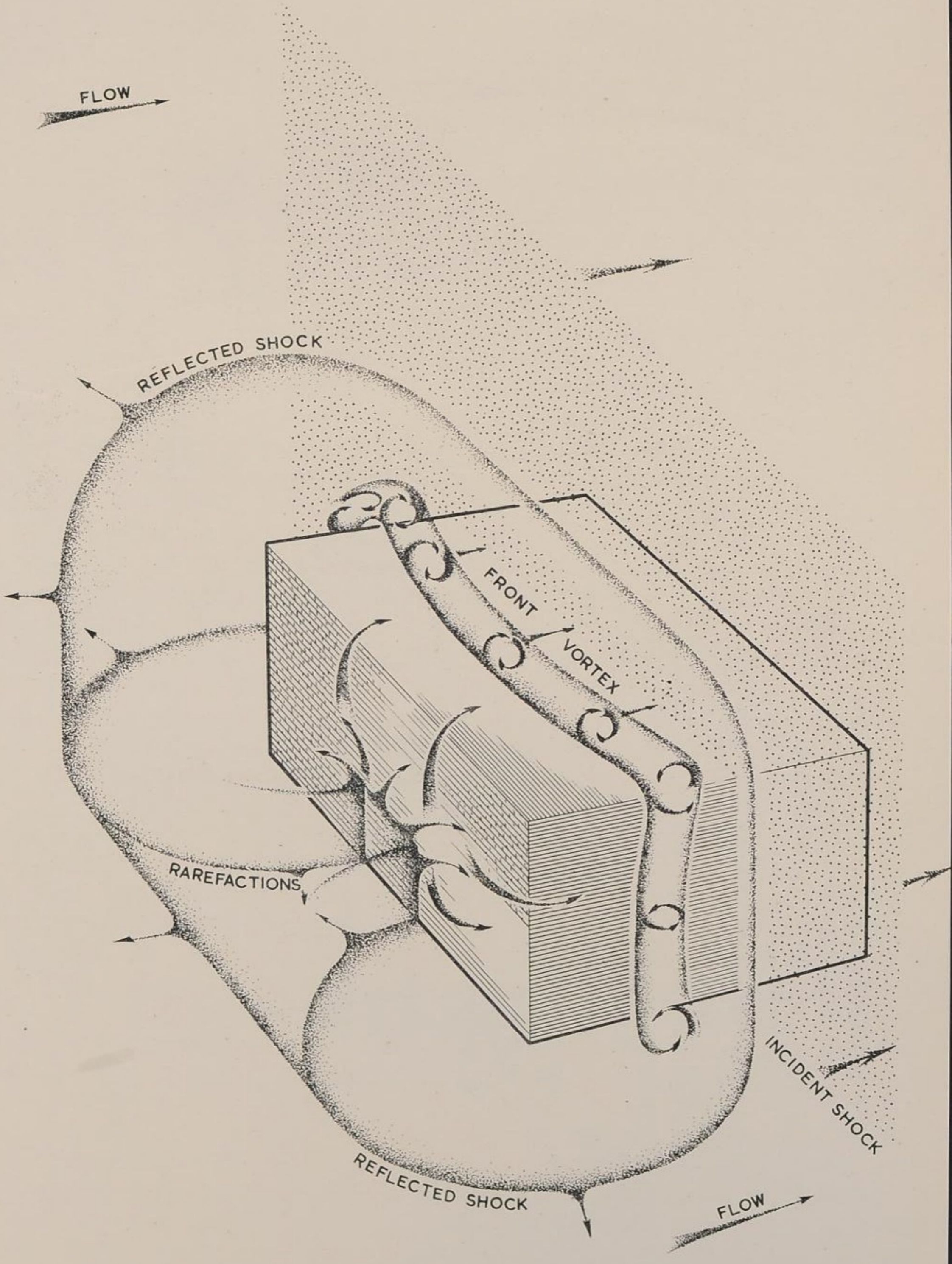
Meanwhile, the incident shock reaches the rear wall of the building and is diffracted round the edges as shown in Figure 2. The flow of air behind the diffracted shock fronts produces, just behind the building, a second vortex which moves away from the rear face as it grows. A rarefaction wave, not shown in the figure, travels backwards from the rear edge across the roof and side walls. After the passage of the diffracted shock waves and their mutual reflections, the external pressure on the rear wall rises until it is substantially the same as in the incident blast wave.

Except for very thin structures, such as free standing walls, the loading on the front and rear surfaces may be considered to be independent.

When the incident shock has completely cleared the target, there remains the drag loading from the dynamic pressure in the blast wave, together with powerful disruptive forces if any of the blast pressure has entered the building and become trapped inside.

References

(1) Effects of Atomic Weapons (Atomic Energy Commission, U.S.A.) 1950, Chapter V A - Air blast damage: general principles.
(2) Atomic Weapons Research Establishment, Report No. E5/55 (Secret/Discreet), gives twelve references to experimental work on the blast loading of structures.



INTERACTION OF A SHOCK FRONT WITH THE FRONT OF A RECTANGULAR BUILDING

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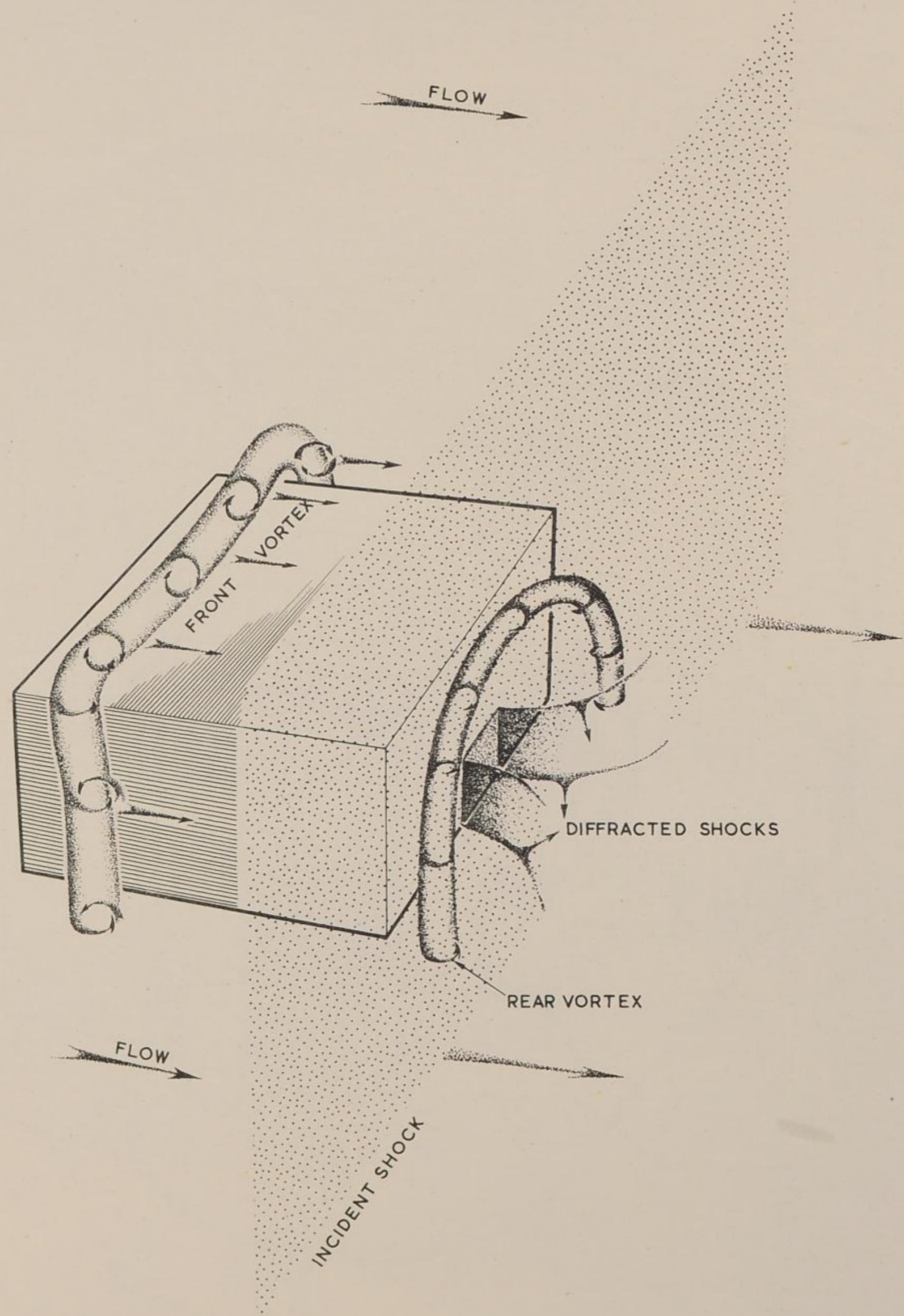

DIFFRACTION OF A SHOCK FRONT OVER THE
REAR WALL OF A BUILDING

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2.2. Panel loadings in a rectangular frame building

2.2.1. Front wall

A typical loading curve giving the variation of static over-pressure with time at a point on the wall of a rectangular building facing the oncoming blast wave is shown in Figure 1. The loading curve consists of three sections: AB - the reflection phase, BC - the rarefaction phase, and CD - the flow phase. Empirical equations have been derived for each of these three phases.

The notation used is as follows:-

W = Total yield of weapon (kilotons.)

p_s = static overpressure (p.s.i.)

P_s = peak static overpressure (p.s.i.)

P_r = Normal reflection pressure corresponding to P_s (p.s.i.)

P_{sg} = Initial stagnation overpressure (p.s.i.)

G = greater of the height or half-width of the building (feet).

S = lesser of the height or half-width (feet.)

D_1 = distance of the point considered from the nearest edge (feet.)

$\frac{1}{\alpha}$ = duration of positive phase of incident blast wave (seconds.)

t_1 = time of arrival of rarefaction wave (seconds) i.e. the time for a sound wave behind a shock p_r to travel a distance D_1.

t = time from arrival of the shock front at the point considered (seconds)

A graph of the initial stagnation pressure P_{sg} as a function of the peak over-pressure P_s is given in Section 1.3 Figure 1, and t_1 can be calculated from the sound velocity c_r which is given as a function of P_r in Figure 2.

During the reflection phase AB, (Figure 1)

$$p = P_r (1 - \alpha t)e^{-\alpha t} \qquad (2.2.)$$

For the remainder of the positive phase BD

$$p = P_x (1 - \alpha t)e^{-\alpha t} + P_y [1 - \beta (t-t_1)] e^{-m \beta (t-t_1)} \qquad (2.3)$$

where $P_x = P_s + \frac{1}{5}\left(1 + \frac{4\,D1}{S}\right)\ (P_{sg} - P_s)$ (2.4.)

and $P_y = (P_r - P_x)\ (1 - \alpha\ t_1)\ e^{-\alpha t_1}$ (2.5.)

The values of m and β are given by

$$m = 1.29 - 0.017\ \frac{D_1}{W^{\frac{1}{3}}} \qquad (2.6.)$$

$$\frac{1}{\beta} = 0.0012G - 0.0009D_1 \qquad (2.7.)$$

The family of curves given in Section 2.2.2. Figure 3, is used to compute the loading curve from these equations. The curves have the equation

$$y = (1 - x)e^{-mx}$$

In solving equations (2.2) and (2.3) the following values are used:-

(2.2) $m = 1,\quad y = \frac{p}{Pr},\quad x = \alpha t$

(2.3) first term, $m = 1,\ y = \frac{p}{P_x},\quad x = \alpha t.$

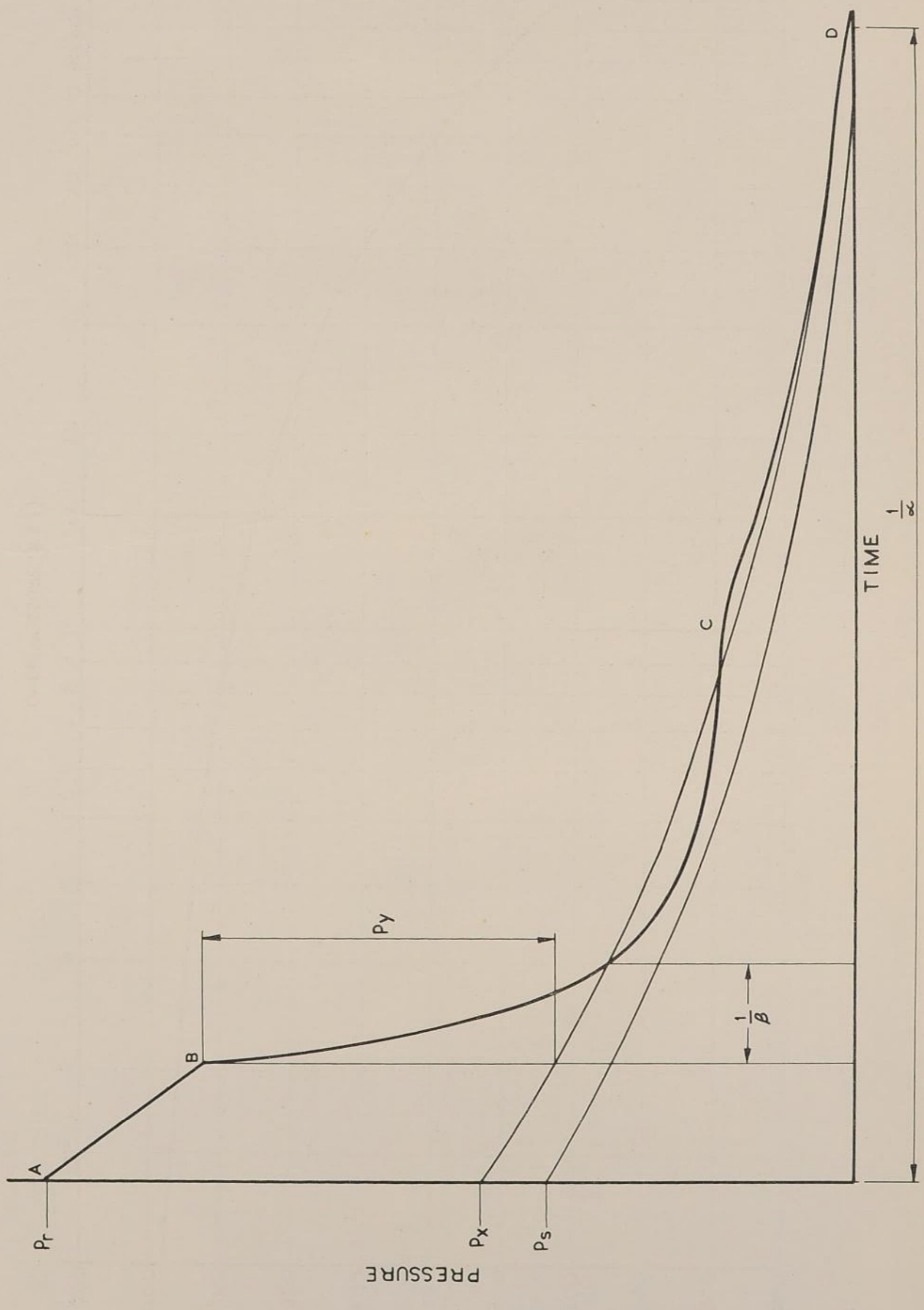
(2.3) second term, $y = \frac{p}{P_y}\quad x = \beta\ (t - t_1)$, and

m is obtained from the equation (2.6).

Loading curves calculated by this method are compared with the results of small scale experiments in reference (1) from which the material in this section has been taken. In all cases the agreement between the curves and experimental results is within 10%.

References

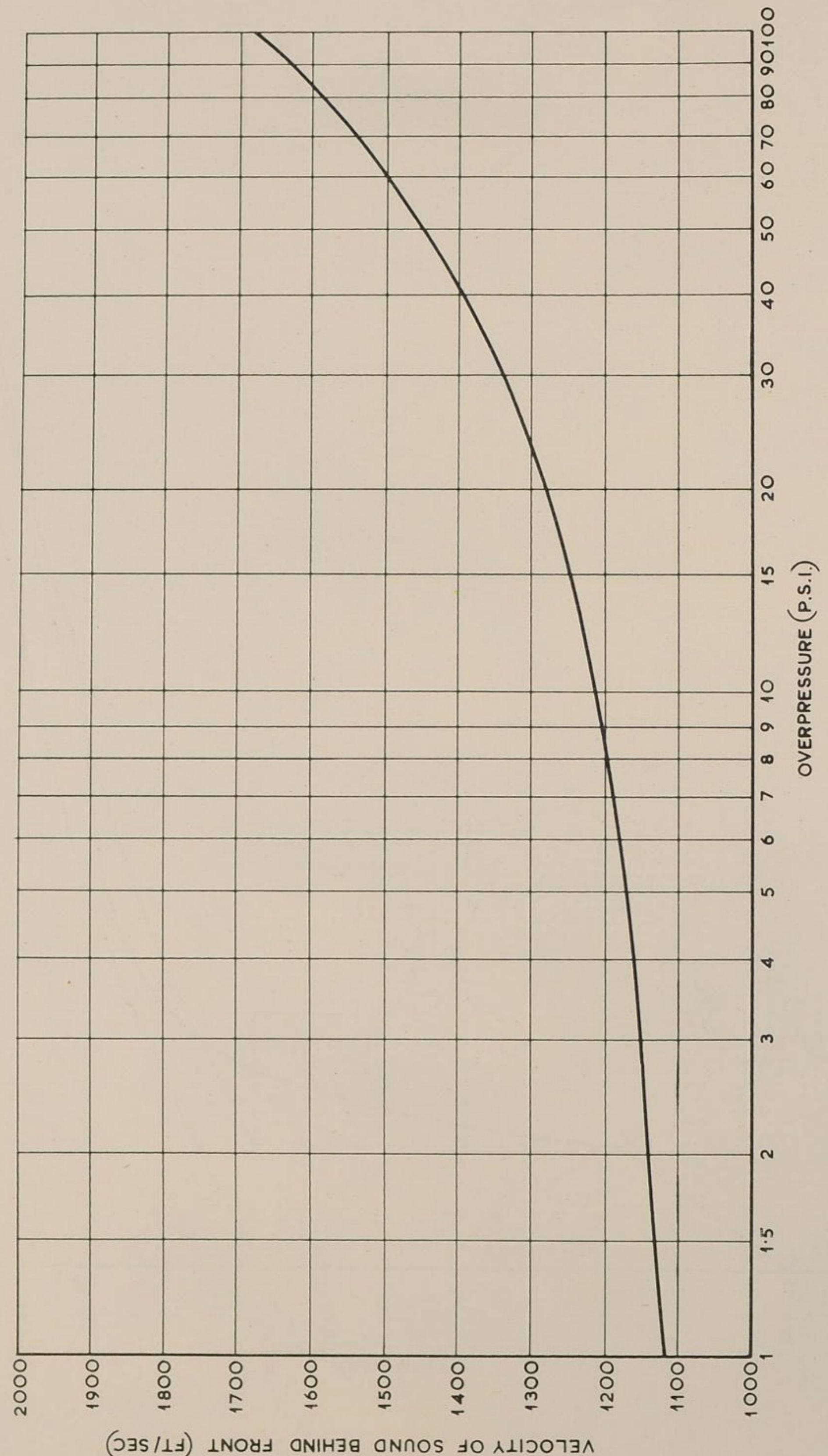
(1) AWRE Report No. E5/55 (Secret/Discreet) October 1955.
The Loading of Buildings by a Large Scale Blast Wave, Part I. Samuels D.E.J. and Rowe, R.D.



LOADING ON THE FRONT WALL OF A BUILDING

CONFIDENTIAL

D.N.W.
AUG. 1957



VELOCITY OF SOUND BEHIND SHOCK FRONT AS A FUNCTION OF SHOCK OVERPRESSURE

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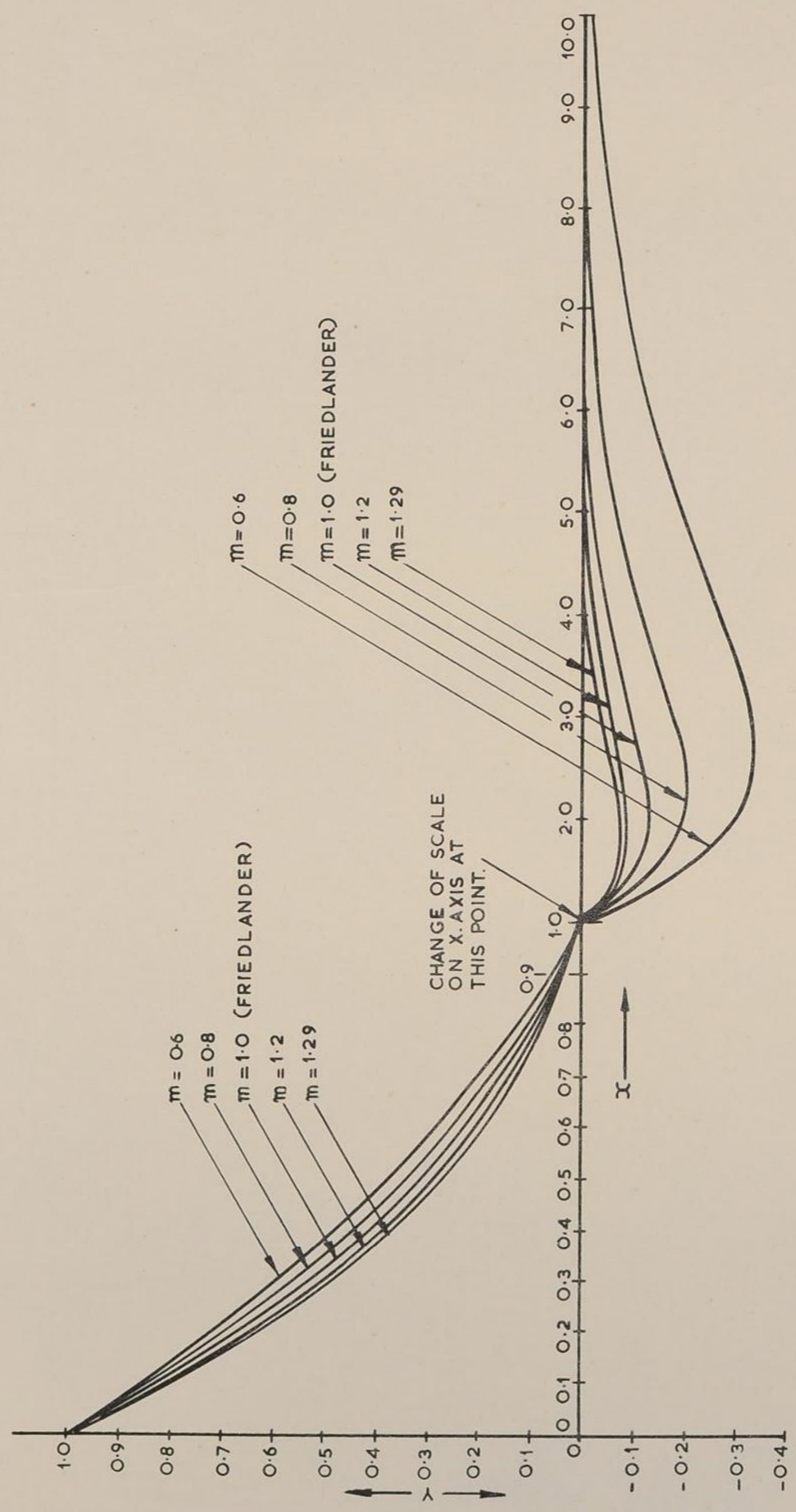
SEPT. 1957



GRAPH OF $Y = (1-x)e^{-mx}$

2.2.2. Rear wall

Figure 1 shows the main features of the time sequence of the static overpressure loading at a point on the rear wall of a rectangular structure. The time origin is taken as the instant at which the incident shock front reaches the rear edge of the building. The first diffracted shock reaches the point under consideration at A on the graph, followed by others until a sharp dip in the loading curve at B marks the onset of the rear vortex (see Section 2.1 Figure 2.) As the vortex moves away from the building the pressure rises and the flow phase CD follows. In general the pressure in this phase is rather higher than in the incident blast wave. The influence of the vortex is greatest at the edges of the wall and becomes negligible at about $\frac{1}{3}$ of the distance from the edge to the centre of the wall.

The above description is based on the results of experiments at the Atomic Weapons Research Establishment (1, 2) in which small-scale model buildings were exposed to the blast from a high explosive charge. An empirical analysis similar to that presented for the front wall in Section 2.2.1 has been undertaken. It has been found that for values of incident shock overpressure P_s in the range 3 to 20 p.s.i. the initial value of the shock diffracted through 90° is $0.37\ P_s$. The diffracted shocks decay as they expand into the space behind the building according to the equation

$$p = 0.37\ P_s \left[1 + \frac{0.103\ d}{W^{\frac{1}{3}}}\right]^{-\frac{1}{2}} \qquad (2.8)$$

where d is the distance in feet travelled by the diffracted shock from the edge of the wall and W is the total yield of the explosion in kilotons.

This function is shown graphically in Figure 2. For values of P_s up to about 20 p.s.i. the interaction of diffracted shocks may be treated as additive. The correction which may have to be applied in the case of stronger shocks follows from normal theory.

The time of arrival of the individual shocks at a point is best estimated by taking the final strength of the shock from Figure 2 and assuming that it has travelled through undisturbed air at atmospheric pressure. The various errors introduced by these assumptions approximately cancel out.

Empirical relationships to represent the vortex effects have recently been worked out Reference (3), but at interior points of the wall the pressure behind the diffracted shocks follows the Friedlander form given in equation (1.2). At any point of the wall there will be four diffracted shocks, the one from the roof and its reflection from the ground, and one from each side. The equation of the loading curve is therefore

$$p = \sum_{i=1}^{4} p_i \left[1 - \alpha(t - t_i)\right] e^{-\alpha(t-t_i)} \qquad (2.9)$$

Each term of the summation starts at time t_i, and α is the reciprocal of the duration of the positive phase of the incident blast wave.

References

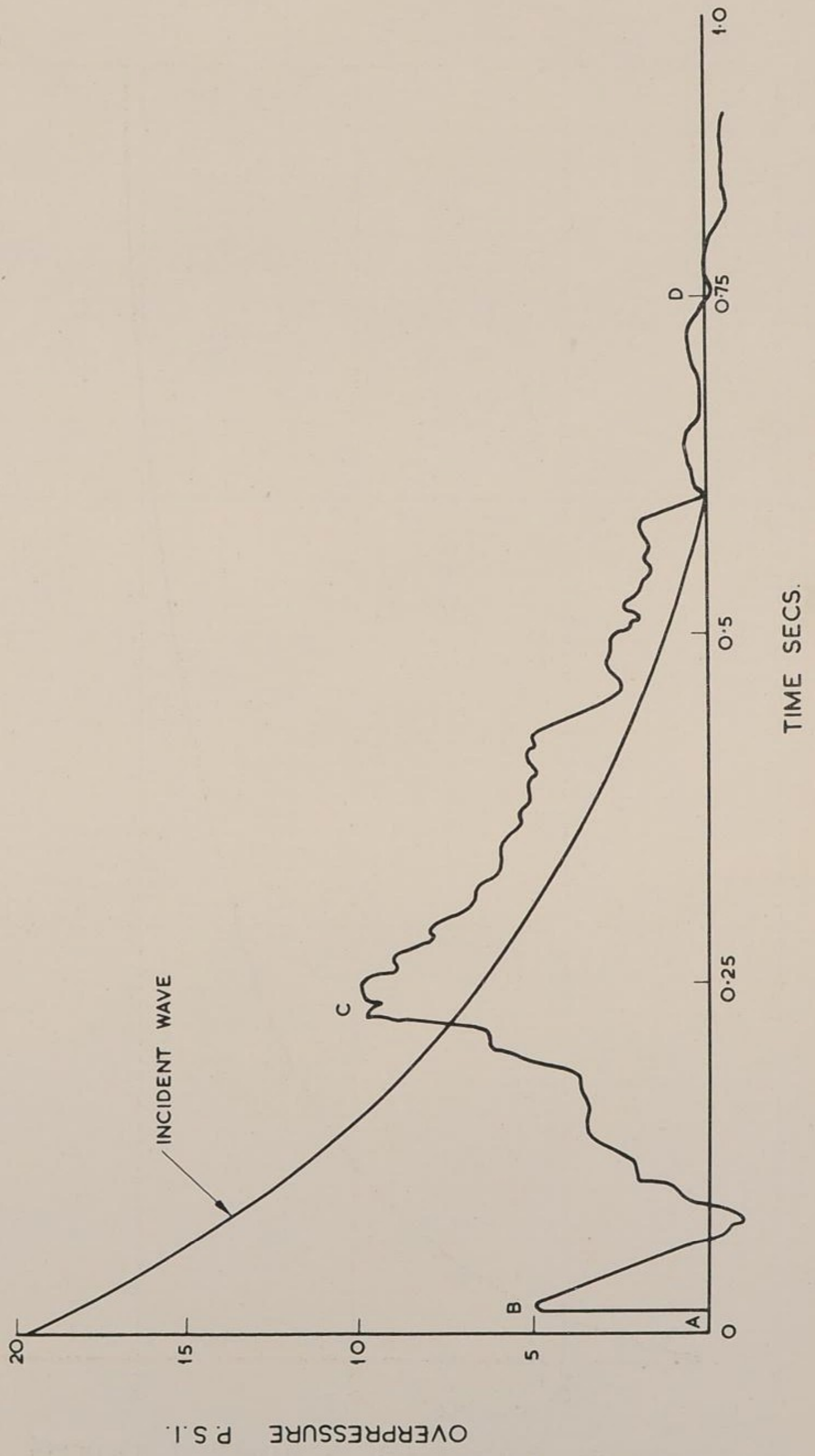
(1) Atomic Weapons Research Establishment Report No. E2/55

April 1955. (Confidential)

Model Experiments on the Loading of the Individual Plane Wall Panels of a Four Storey Block of Flats due to Atomic Blast. Rowe, R.D. et alia.

(2) A.W.R.E. Foulness Laboratory Note No. 3/53 (Confidential)

(3) A.W.R.E. Report No. E -/57. Loading of buildings by a large scale blast wave. II. Rowe, Samuels and Walford. (Confidential)



LOADING ON THE REAR WALL OF A BUILDING

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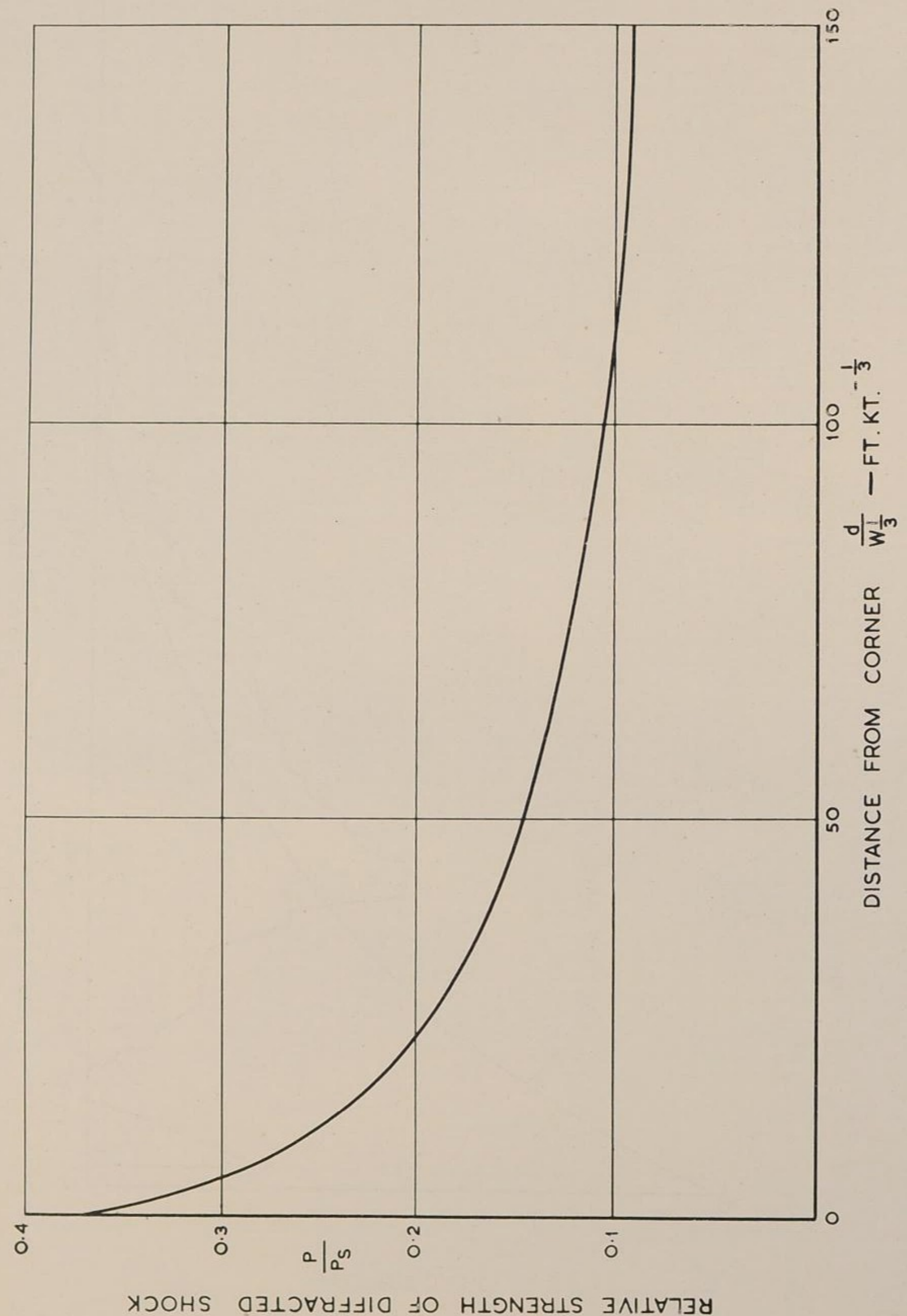

ATTENUATION OF A DIFFRACTED SHOCK

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2.2.3. Roof and sides

The loading on the roof and side walls of a rectangular structure is not much different from the static overpressure in the incident blast wave, and it is recommended that this be used in calculating blast pressure effects. The concurrent drag and vortex effects cannot easily be analysed.

The only experimental data available for three-dimensional structures are given in A.W.R.E. Report No. E2/55 (Confidential).

2.2.4 Other orientations

Where P_s is the incident shock overpressure, and p_r the corresponding reflected pressure, the value $\frac{p_r}{p_s}$ is known as the reflection coefficient, and for face-on reflection has the value

$$\frac{p_r}{p_s} = 2. \frac{4p_s + 7P}{p_s + 7P}$$

as given in section 2.1.

According to the theory of shock wave reflection at a rigid surface, the reflection coefficient varies with the angle of incidence, and the reflected shock pressure reaches a maximum around the transition angle from regular to Mach reflection. This has been confirmed by optical measurements of shock velocities in a shock tube (1). It was found, however, that the reflected or Mach shock is followed by a strong rarefaction which causes the pressure to fall very rapidly behind the shock front. Measurements of pressure on the wall, using relatively large piezoelectric gauges show a monotonic decrease of pressure as the angle of incidence changes from 0^o to 90^o (1.2). The Princeton (1) and AWRE (2) investigations used almost the same shock strength, and the mean of both sets of results is given in Figure 1, corresponding to $p_s = 3.5$ p.s.i. There is no published data for other shock strengths and it is recommended that a curve proportional to that in Figure 1 be used, the value of the reflection coefficient for zero incidence being obtained from equation (2.1).*

No information is available on the pressure loading on a wall inclined at an angle and facing away from the blast, but it is probable that the effect would be intermediate between the conditions, discussed in Sections 2.2.2 and 2.2.3, for the rear wall and for the roof and sides.

References

(1) O.S.R.D. Report No. 6271 (1945) (Confidential/Discreet)

(2) A.W.R.E. Report No. E5/53 (Confidential)

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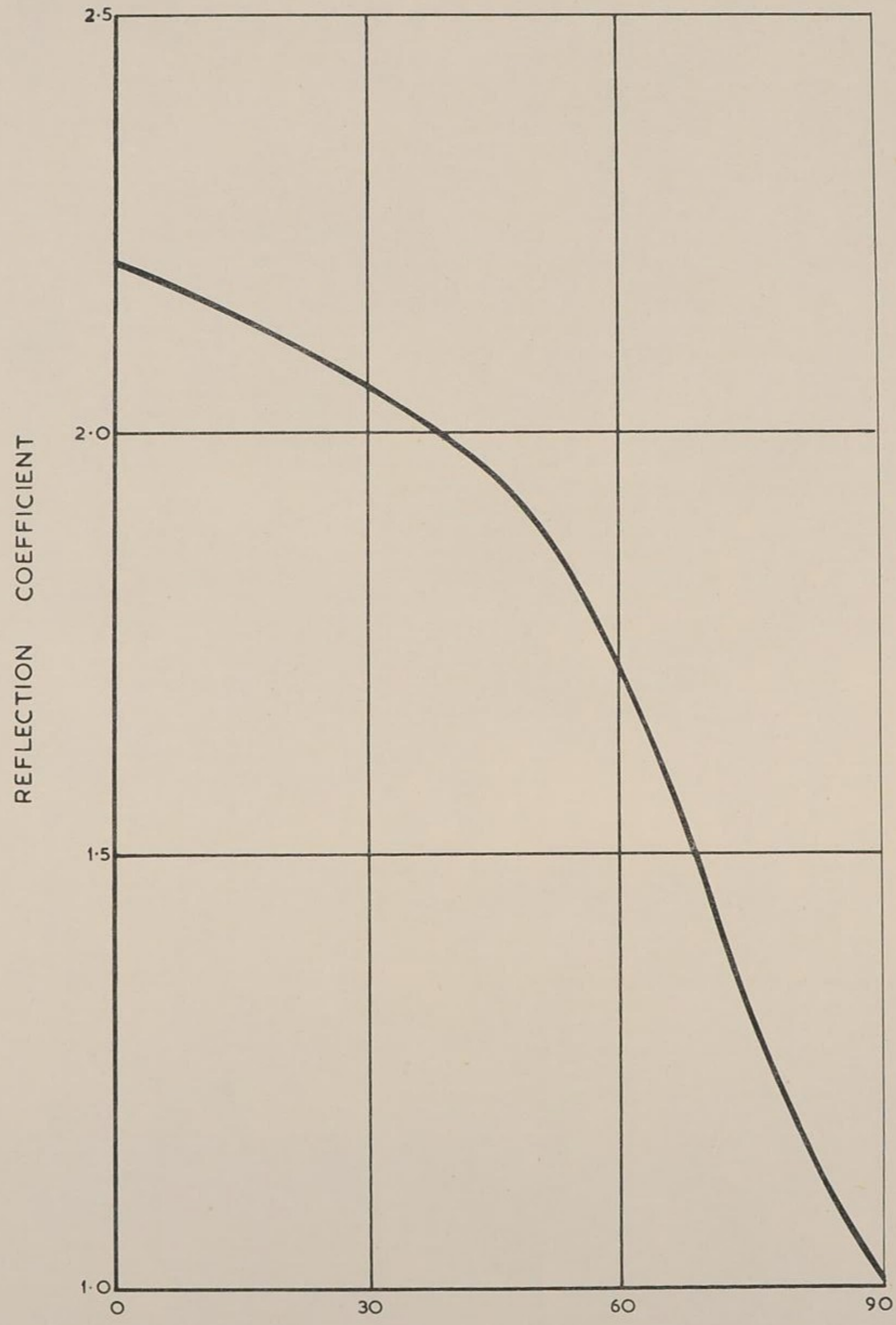
* Chapter 3, pages 76-77, of the Effects of Atomic Weapons, U.S. Government Printing Office 1950 gives a treatment which has been found not to accord with practice, and should therefore be disregarded in this connection.



REFLECTION COEFFICIENT AT VARIOUS ANGLES FOR A SHOCK OVERPRESSURE OF 3·5 P.S.I.

2.3 Translational and Overturning Forces

In order to obtain the resultant static force acting on a structure as a whole, it is necessary to determine the total force acting on the front and rear surfaces as a function of time, and to subtract one from the other, taking into account the time taken by the blast wave to travel the length of the structure. In some cases drag forces must also be considered. (see Section 2.4).

The force on the front surface can be found by dividing the surface into a grid of squares, and calculating the loading curve for the centre of each square by the method given in Section 2.2.1. As the only quantity in the loading formulae which varies with the position on the surface is the distance from the nearest edge, D_1 only a few calculations are required. For a square surface, a grid of 25 squares would normally be sufficient, giving three values of D_1. The loading at the centre of each square is assumed to represent the average pressure on the square.

As the point loading on the rear surface cannot be calculated accurately at present, the average pressure on the rear surface may be assumed to build up linearly to the incident blast pressure in the time $\frac{ns}{u}$, the empirical coefficient n is read from Figure 1. This figure is taken from reference (1) and is based on two-dimensional shock tube results and three-dimensional data from U.S. atomic weapon trials. U is the velocity of the incident shock wave as given in Figure 2, and S is the smaller of the height and the half-width of the surface.

Owing to the decay of pressure in the blast wave and the time lag between the loading of the front and rear surfaces, the resultant force on a structure in the flow phase will be directed towards the explosion if the structure is large enough. As an approximate rule this will occur if (L + 2S) is greater than $60W^{\frac{1}{3}}$, where L is the length of the structure in feet, S is the smaller of the height and half-width (also in feet) and W is the total yield of the weapon in kilotons.

Free-standing targets will be displaced or overturned by the blast. Such objects are usually small enough for all the blast forces to have passed before the object has moved appreciably. Thus the initial orientation may be taken for purposes of calculation; and moreover the loading will be such that drag will play an important part.

Sliding will occur, and for sufficient impulses, tipping or tumbling. The distinction, in the notation of Figure 3 is given by

$$\frac{T^2}{2I_A} \leqslant mgd\,(1-\sin\theta_o) \qquad (2.10)$$

for sliding, and for overturning

$$\frac{T^2}{2I_A} \geqslant 2\,mgd\,(1-\sin\theta_o) \qquad (2.11)$$

intermediate cases being in doubt.

In these equations T is the impulse, and I_A the moment of inertia of the target about the axis through A.

Evaluation of equations (2.10) and (2.11) is made in the following manner.

$$T = Ah \left[I_H + I_D - \frac{I_D}{10} \right] \quad (2.12)$$

where h is the height of the centre of pressure, A is the side-on presented area of the target (assumed to be constant), I_H is the net translational static impulse, and I_D equals the drag impulse.

$$I_H = \frac{3}{2} \left[\frac{f}{C_r} (p_r - p_s) + \frac{b}{C_o} p_s \right] \quad (2.13)$$

where f and b are the minimum distances from an edge to the centre of the front and rear faces respectively of the target in the side-on position, and C_r is the velocity of sound in the initial reflected pressure region and C_o the velocity of sound in undisturbed air (1130 ft/sec.).

Also, $$I_D = \frac{1}{5} P_d \; t_p \quad (2.14)$$

where t_p is the positive duration of the pressure wave.

Further, $$I_A = m \left[\frac{W^2 + \chi^2}{12} + d^2 \right] \quad (2.15)$$

where W is the width of the target and χ is "effective" height for the purpose of calculating I_A.

The target will therefore not overturn if

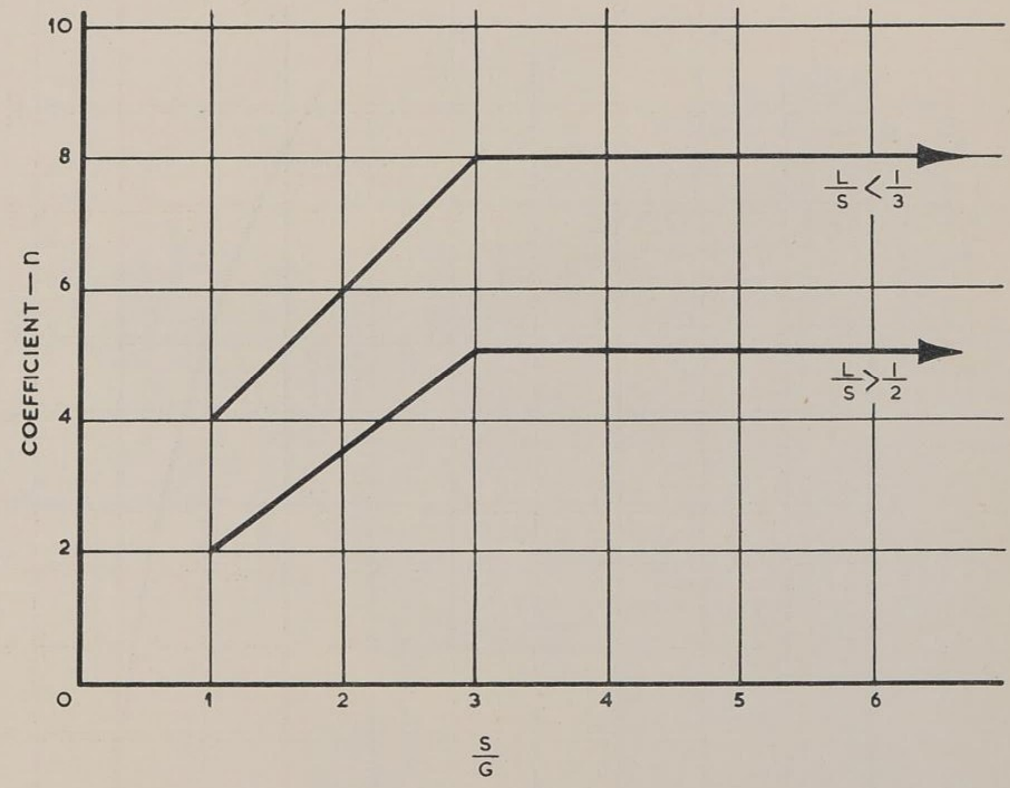
$$(I_H + 0.9\, I_D) < \left[\frac{2I_A \, mgd\, (1 - \sin\theta_o)}{Ah} \right]^{\frac{1}{2}} \quad (2.16)$$

Some applications to the megaton case are given in Reference (2)

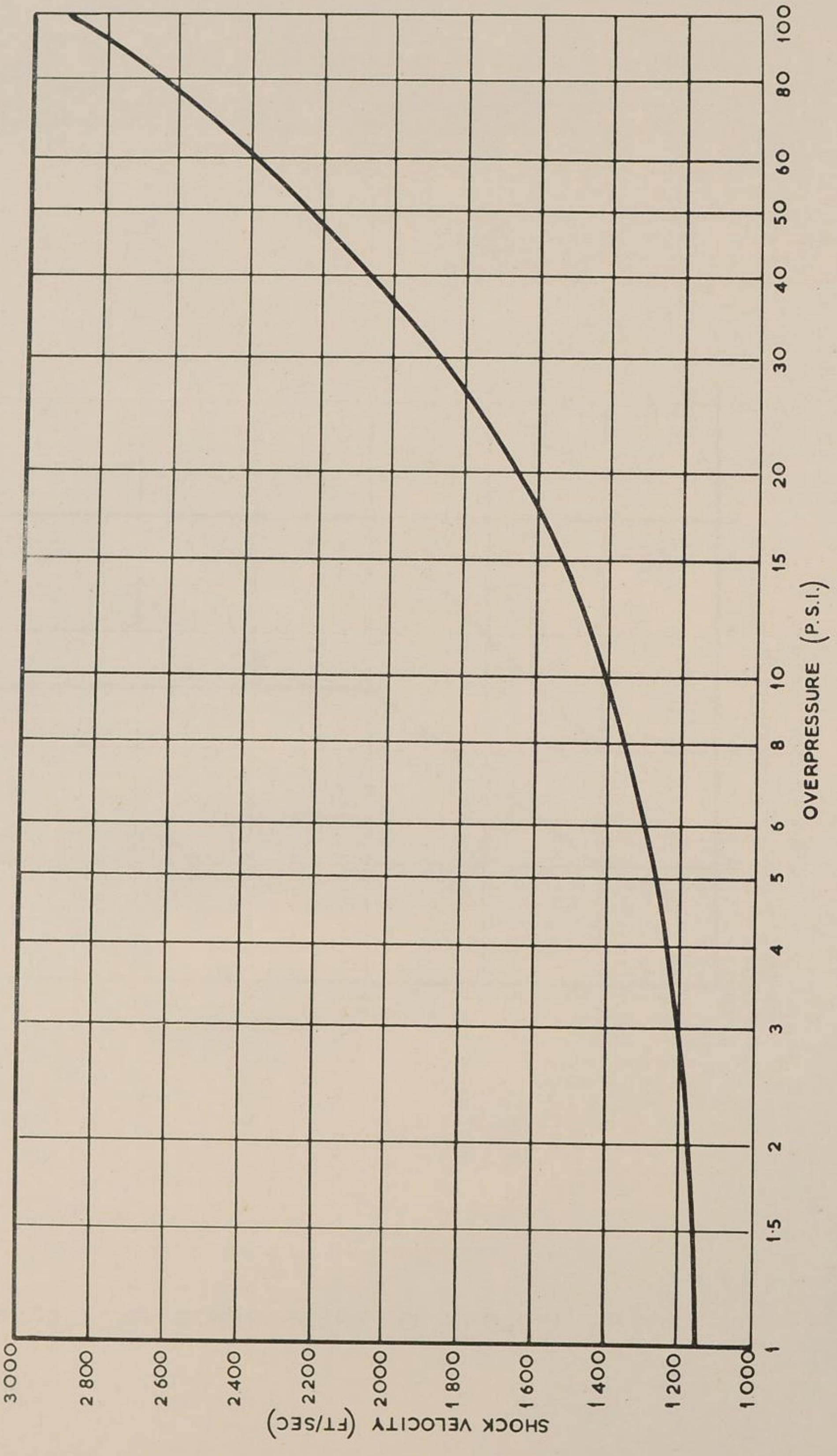
References

(1) Armour Research Foundation Project No. M024-1
Final Report (Report No.18) 1954 (Confidential/Discreet)

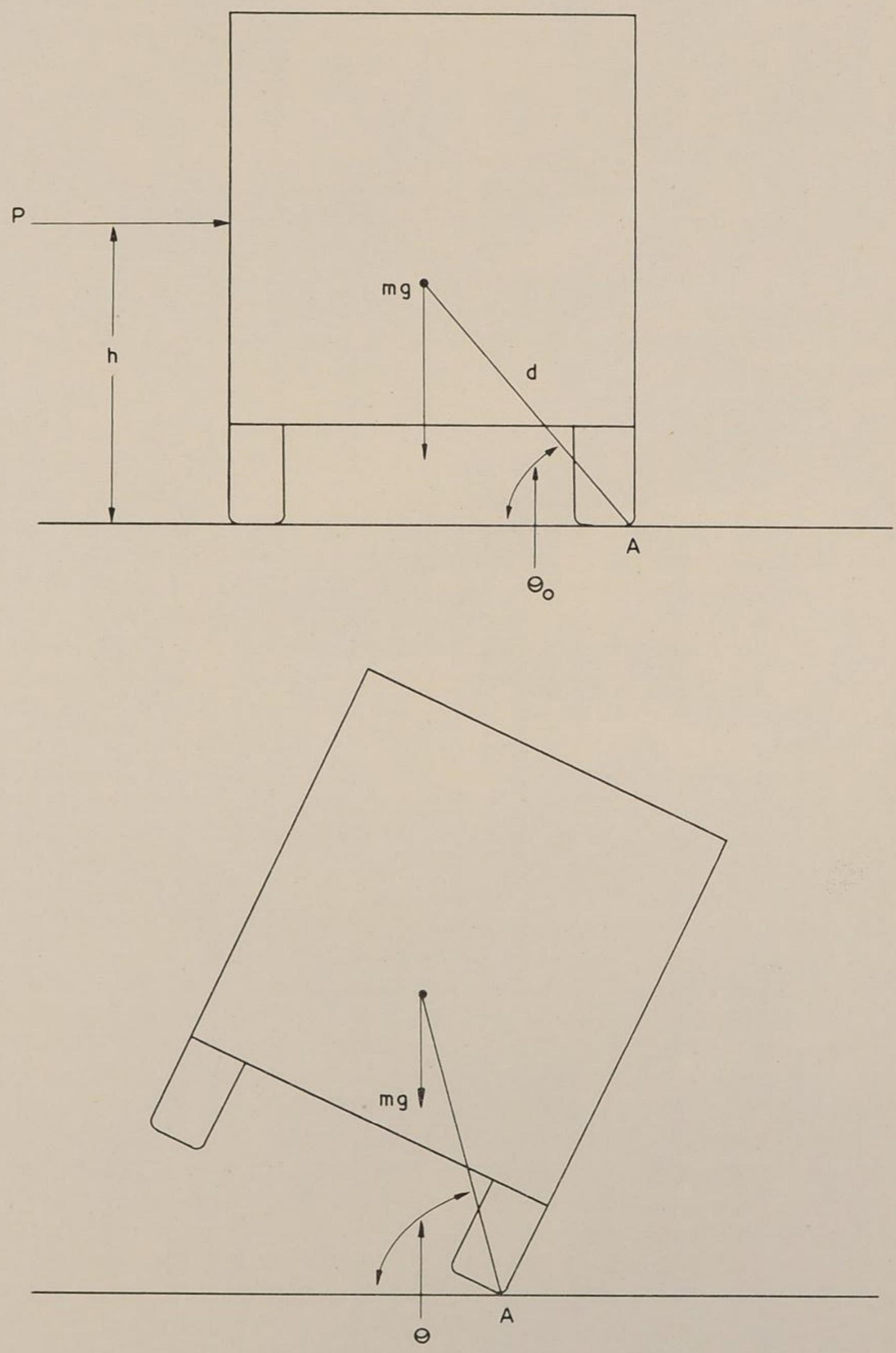
(2) Estimates of some blast wind effects of megaton bombs.
A.W.R.E. Report No.E6/55.
(Secret/Atomic/Discreet (Cleared for Canada))



BUILD-UP OF PRESSURE ON REAR WALL



SHOCK VELOCITY AS A FUNCTION OF SHOCK OVERPRESSURE



OVERTURNING A FREE-STANDING TARGET

2.4. Drag Structures

Structures whose size is small compared with the region covered by the positive phase of the blast wave at a given moment are soon enveloped in the pressure wave so that its effects tend to be reduced in comparison with those due to the drag of the blast wind. This particularly applies to long thin structures such as chimney stacks or open steel frameworks, or to many types of vehicles and field equipment. Moreover it will be seen that the relative importance of drag forces increases with the yield of the weapon, affecting most targets in the case of megaton weapons.

This drag force on any given portion of the target is the product of the local dynamic pressure p_d, the presented area, and the drag coefficient for the section, C_d. Values of C_d have been determined for a number of shapes of section for study flows in wind tunnel experiments (1, 2, 3). These values are shown in Figure 1. Forces on complete structures may be approximated by summation of the forces on the separate parts. Detailed information is not available on drag coefficients for transient, variable speed flows.

In the absence of more relevant data, it is believed that the values given in Figure 1 may be used in blast loading calculations without serious error. The value of C_d for cylindrical sections depends on the Reynolds Number of the air flow which is defined as

$$Re = \frac{UL}{\nu} ,$$

where U is the wind velocity, ν the kinematic viscosity (0.0001423 ft^2/sec^2 for air at N.T.P.), and L is a characteristic length such as height or diameter. Figure 1 gives the values of $\frac{Re}{L} = \frac{U}{\nu}$ immediately behind the shock front as a function of shock pressure p_s; The values were calculated for air pressure at 14.7 p.s.i. and temperature 17°C (62°F) ahead of the shock front.

The initial dynamic pressure is given by equation (1.1) and the variation with time in the blast wave by equation (1.4).

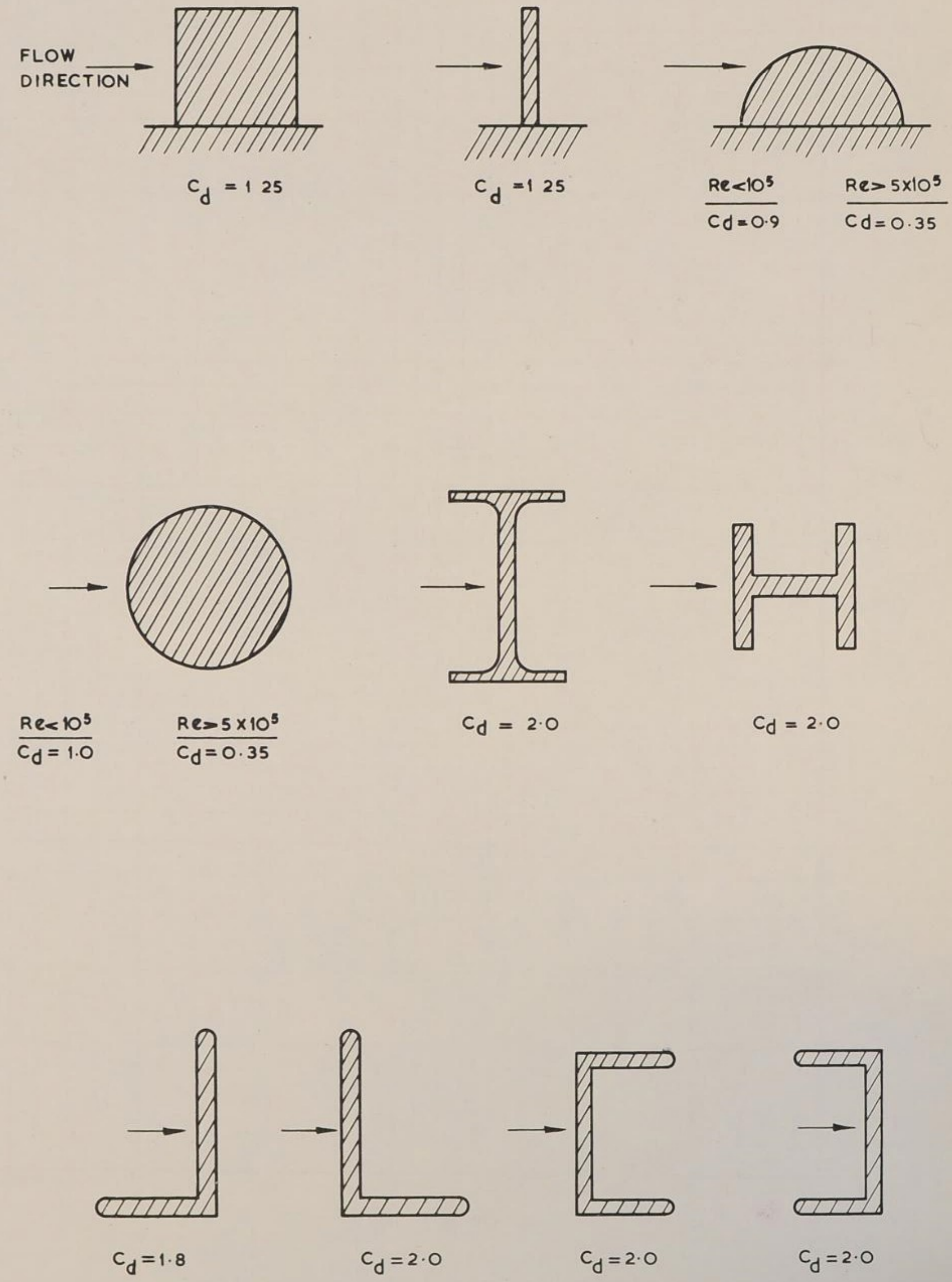
References

(1) Chien, Feng, Wang, Siao. "Wind Tunnel Studies with Pressure Distribution of Elementary Building Forms". Iowa Institute of Hydraulic Research, State University of Iowa.

ONRN 8 onr - 500. 1951.

(2) Howe, G.E. "Wind Pressure on Structures", Civil Engineering Vol.10 (3), March, 1940.

(3) Irminger, J.O.V. and Nkkentved, C. "Wind Pressure on Buildings", Experimental Researches (Second Series); Copenhagen, Ingeniorvidenskabelige Skriftn, 1936.

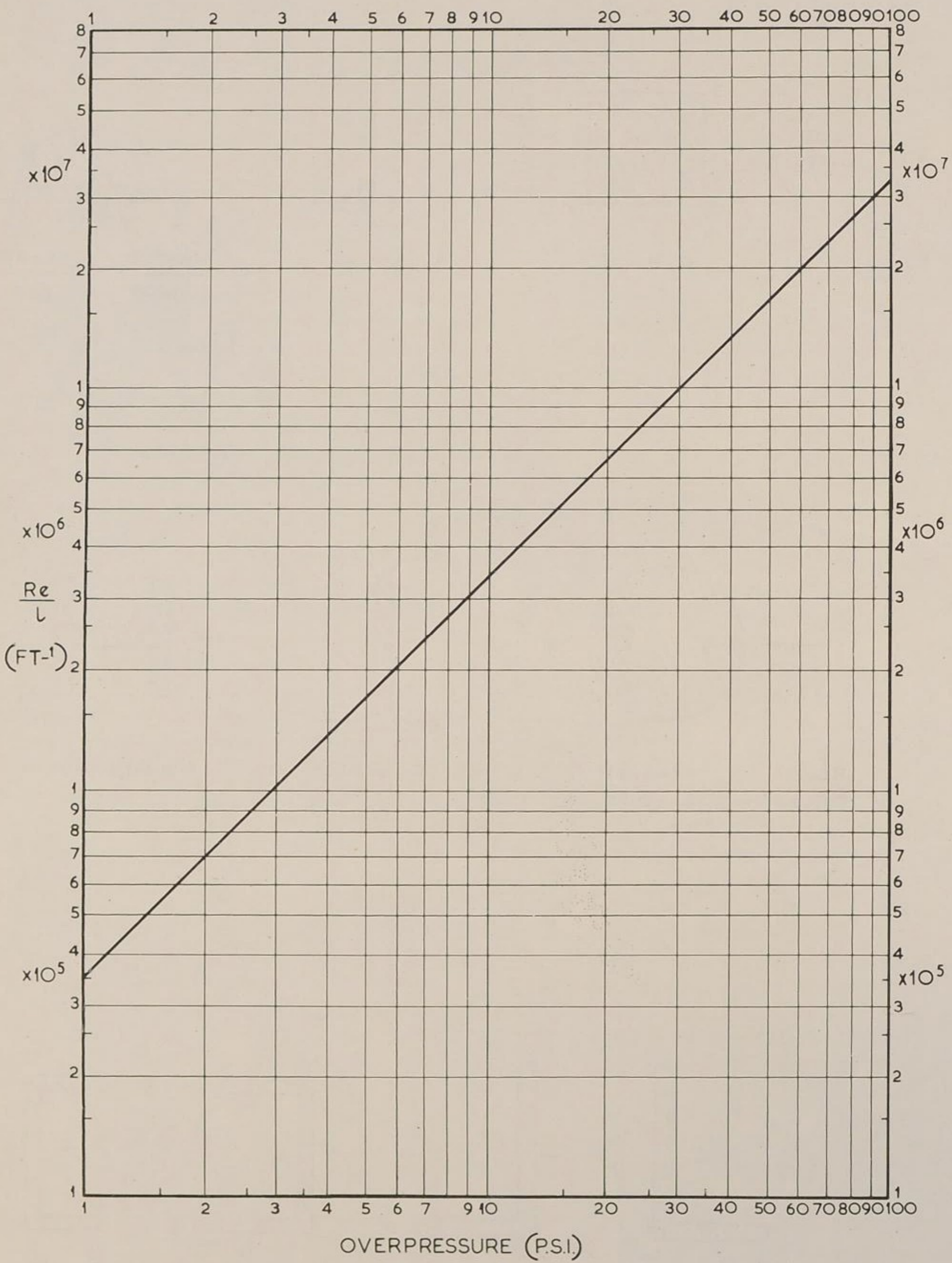


DRAG COEFFICIENTS

UNCLASSIFIED

D1/57
REVISED
FEB. 1959

THIS FIGURE INCORRECT – NEW ONE TO BE ISSUED



REYNOLDS NUMBER PER UNIT LENGTH BEHIND SHOCK FRONT

UNCLASSIFIED

2.5 More Complex Structures

There is very little analytical information available on the blast loading of structures of more complex shape in the three-dimensional case, which is of practical interest. Two-dimensional shock tube studies of a house with a ridge roof have been made at Princeton University (Ref(1)) and A.W.R.E. The main difference between a house with a ridge roof and one with a horizontal roof is in the vortex formation. The front vortex is weaker and two rear vortices are formed, a very strong one behind the ridge and a weak one in the normal position behind the top edge of the rear wall. The loading on the front and rear walls can be approximated by considering an equivalent rectangular structure whose height is equal to the height of the vertical wall plus 2/3 of the vertical distance from eaves to ridge.

The strong vortex behind the ridge will produce a lifting force which will tend to strip off the roofing material. Tiles and slates are likely to become high velocity missiles.

Much of the empirical damage information derived from U.S.Atomic trials is summarised in the form of tables and curves in Chapter 9, mainly from Reference (2).

Recent A.W.R.E. model studies of the effects due to blast entering a building are reported in Reference (3).

References

(1) Princeton University Technical Report II - 6 - 1950

(2) Capabilities of Atomic Weapons. 1 June 1955. AFSWP. Part 2. Damage Criteria. (Secret/Atomic)

(3) AWRE Report E7/57 (Confidential)

CHAPTER 3 MODIFICATION OF BLAST LOADING BY NEIGHBOURING STRUCTURES

3.1. Earth traverse of triangular section

An earth traverse is commonly used to protect buildings from damage by blast and fragmentation weapons. As the space between the wall of the building and the traverse is normally small compared with the height of the building, the blast loading on the building from an atomic weapon is modified by the traverse. The formation of vortices results in a very complex redistribution of the load. Some model scale experiments to investigate this effect have therefore been performed by A.W.R.E. (1).

The model represented a building 70ft. x 50ft. x 16ft. high surrounded by a traverse of the same height and of triangular section with a vertical inner face and a slope of 45° on the outer face. Spacings of 4ft. and 8ft. between traverse and wall were investigated. On the same scale the H.E. charge represented an atomic bomb of about 40KT yield exploded 500ft. above the ground. The incident blast over-pressure on the model was 13 p.s.i., so that the reflection overpressure on the front face would have been 33 p.s.i. without the protection of the traverse. With the 4ft spacing the loading on the side walls of the building was not much affected by the presence of the traverse, the maximum over-pressure being 13 to 15 p.s.i. On the front and back walls, however, multiple reflection occurred between the wall and traverse, the maximum pressure on the back wall being rather higher than on the front wall, presumably because of the strong vortex produced behind the acute angle of the traverse in front of the building. The maximum overpressure was 14 to 18 p.s.i. on the front wall and 16 to 20 p.s.i. on the back wall. In each case the loading curve consisted of a number of peaks and troughs due to the multiple reflections and vortices. Doubling the spacing between the traverse and the wall resulted in maximum overpressures about 10% higher. It appears that the effect of close spaced blast walls or traverses of this shape is to decrease the otherwise high reflection overpressure on the front surface of the target, while increasing rather than decreasing the load on the rear.

In considering the shielding effect of other configurations it must be realised that the walls of the building will receive at least the static overpressure in the incident blast wave. This condition will be approximately obtained with the type of traverse described above when the space between the building and the traverse is very small (less than 1/10th of the height). As the separation is increased the reflections between wall and traverse will become stronger. The effect will be similar to that described in the next section (3.2) for adjacent buildings. If the height of the traverse is less than that of the building, the front wall will experience a greater loading, and if the height is more than that of the building, there will be a stronger reflection off the traverse at the back of the building. The most effective blast shielding would therefore probably be obtained with a traverse equal in height to the building, with a vertical inner face and as small a separation from the building as is practicable.

In some cases, the earth is mounded in contact with the wall of the building, and will add considerably to the effective mass of the wall. This will increase the response time of the wall and may give some degree of structural protection if the duration of the blast loading is not too great (see chapter 6). For long duration blast waves (from weapons in the megaton range) the main structural protection would be due to the considerable reduction in loading on account of the

streamlining effect of the mounding.

Reference

(1) A.W.R.E. - unpublished data.

3.2. Adjacent Rectangular Structures

Some screening from the blast wave is to be expected if other buildings are interposed between ground zero and the target under consideration, though the effect will be diminished by diffraction of the blast wave around the screening buildings. The effect has been studied in two dimensions in the Princeton University shock tube, (1) using two similar rectangular blocks at several different separations. In this work the pressure behind the shock front was constant.

Similar experiments using explosive charges have been conducted at A.W.R.E. (2) and (3). Two-dimensional and three-dimensional models were used in which pressure gauges were mounted. The charge represented an atomic bomb of about 40 KT R.C. yield exploded 500ft. above the ground. On the same scale the models represented rectangular buildings 27ft. high and 27 ft. deep, the three-dimensional buildings being 33ft. wide and the two-dimensional building was of such a width that no signal from the ends reached the pressure gauges during the positive phase of the blast wave. The centre lines of the models were in a line with ground zero, and separations of 0.5, 1, 2 and 4 times the height were used. The peak over-pressure in the incident blast wave was 12 p.s.i. in all cases.

In both the two and three-dimensional cases a shock wave is reflected back and forth between the two buildings producing multiple peaks in the pressure on the walls. The reflections are more persistent in the two-dimensional case as there is less chance of diffraction round the buildings. In both cases the peak overpressure on the front wall of the rear building at the smallest separation is 30-40% less than that on isolated buildings. The results for a separation equal to the height of the buildings are reproduced in Figure 1, in which the variation of average over-pressure on the walls with time is shown by a continuous line and the loading on an isolated building by a broken line. The peak over-pressure on the back wall of the front building is doubled. At greater separations the shielding effect on the rear building is negligible, but the reflected pulse still has a significant effect on the front building.

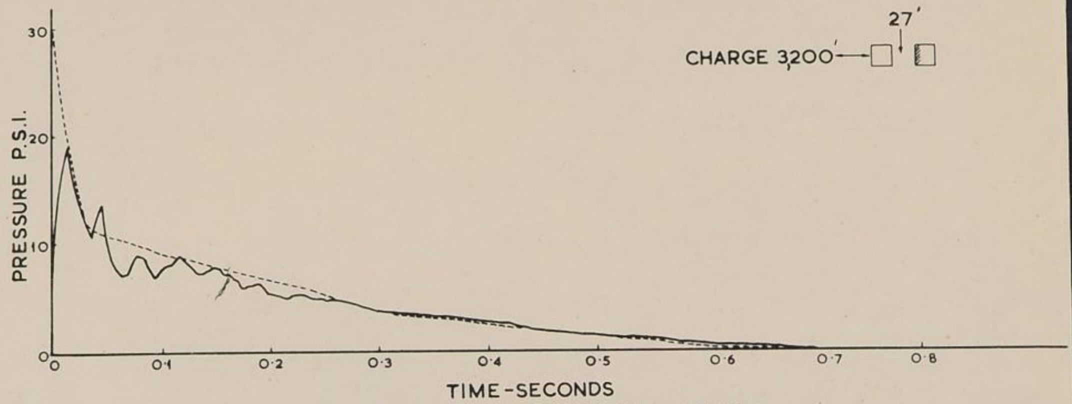
It is worthy of note that the translational force on both buildings is reduced by their mutual interaction, the pressure on the back wall of the front building being increased, and that on the front wall of the rear building being reduced.

References

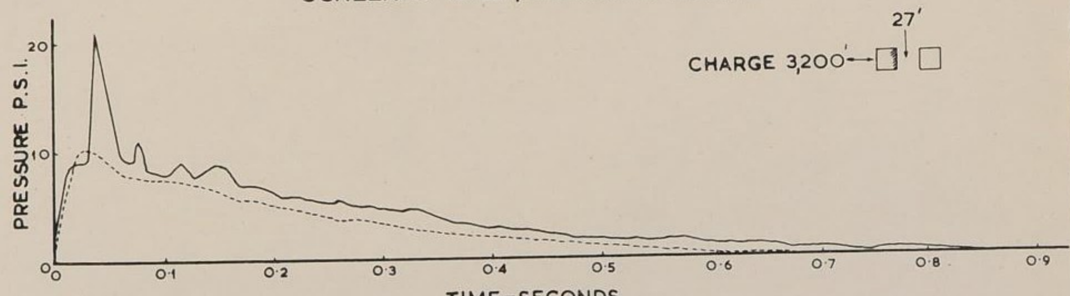
(1) Princeton University, Department of Physics. Technical Report II-3. 1950.

(2) A.W.R.E. Foulness Division Laboratory Note 1/55 (Confidential) and A.W.R.E. Report No. E4/57 (Confidential)

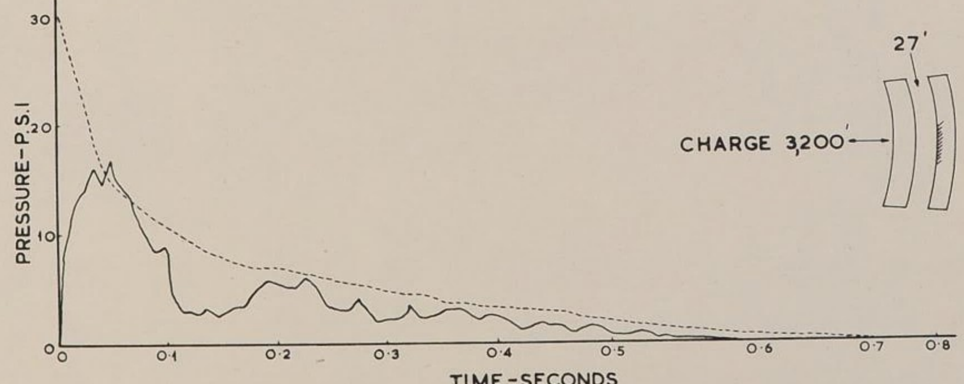
(3) A.W.R.E. Report No. E8/57 (Confidential)



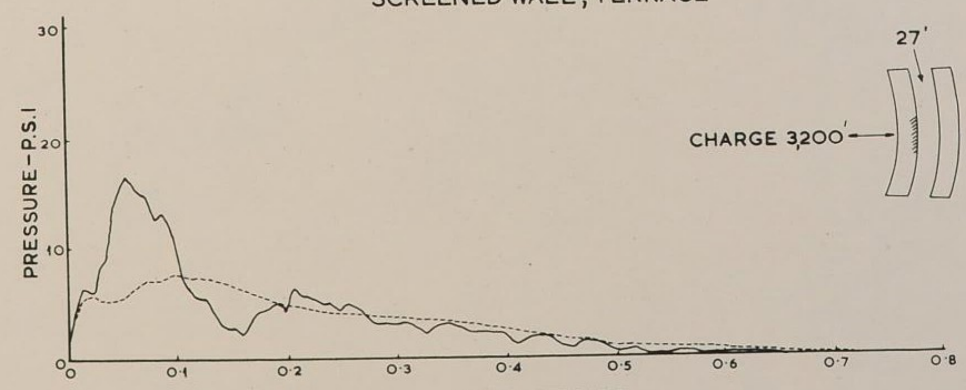
SCREENED WALL, DETACHED HOUSE



SCREENING WALL, DETACHED HOUSE



SCREENED WALL, TERRACE



SCREENING WALL TERRACE

THE EFFECT OF SHIELDING ON BLAST LOADING

SEPARATION EQUAL TO HEIGHT OF BUILDING

3.3. Earthworks to protect drag-sensitive targets

Targets, such as most military field equipment, which are relatively insensitive to overpressure, may be considerably protected from the dynamic effects of blast by earthworks. Effective shielding design must prevent the drag forces from impinging directly upon any part of the target item. Of possible shields, only earth mounds and trenches have proved themselves sufficiently immune against the effects of the blast. Optimum designs are still under study, but it is expected that if the drag loads can be largely eliminated, the vulnerability of the equipment will be reduced to its vulnerability to the crushing effect alone. In the Mach region of blast reflection this will probably produce only light damage at ranges where damage would otherwise have been severe. The severe isodamage curve would thus become a Light Damage contour for damage assessment purposes.

British experience of the protection given to stores by pits and mounds at Operation Totem is summarised in Section 4.16 of Reference (2).

A small mound between Ground Zero and a side-on fighter aircraft gave negligible protection, (Reference (3)).

References

(1) Reduction of Blast Damage by Shielding
Presentation by Major Richard J. Hesse at Conference on the Effects of Blast on Military Field Equipment, A.F.S. W.P. 29th February, 1956. (Secret/Atomic)

(2) The effects of an atomic explosion upon Ammunition. Operation Totem. Major L. Cave, R.A.O.C. A.W.R.E. Report T84/54 (Secret)

(3) The effects of Totem 1 explosion on aircraft of stressed skin construction. Offord and Noble A.W.R.E. Report T112/54 (Confidential)

CHAPTER 4. ENTRY OF BLAST INTO STRUCTURES

4.1. Entry through Large Apertures (the case of a rectangular box)

4.1.1. Immediate Entry through Doors, Windows, etc.

The failure time of glass windows is so short that they can be assumed to offer no resistance to the entry of a blast wave impinging on a building. If the proportion of window openings in the wall is at all large, a significantly strong shock may enter the building. An estimate of the shock strength inside such a building has been made by the Armour Research Foundation(1). Their estimate is based on experimental results from the Princeton shock tube, Sandia Corporation H.E. tests, and the Operation Greenhouse atomic weapon test. Their estimate is given graphically in Figure 1 together with the experimental data, which are seen to be rather scanty. The curves should therefore be used with caution.

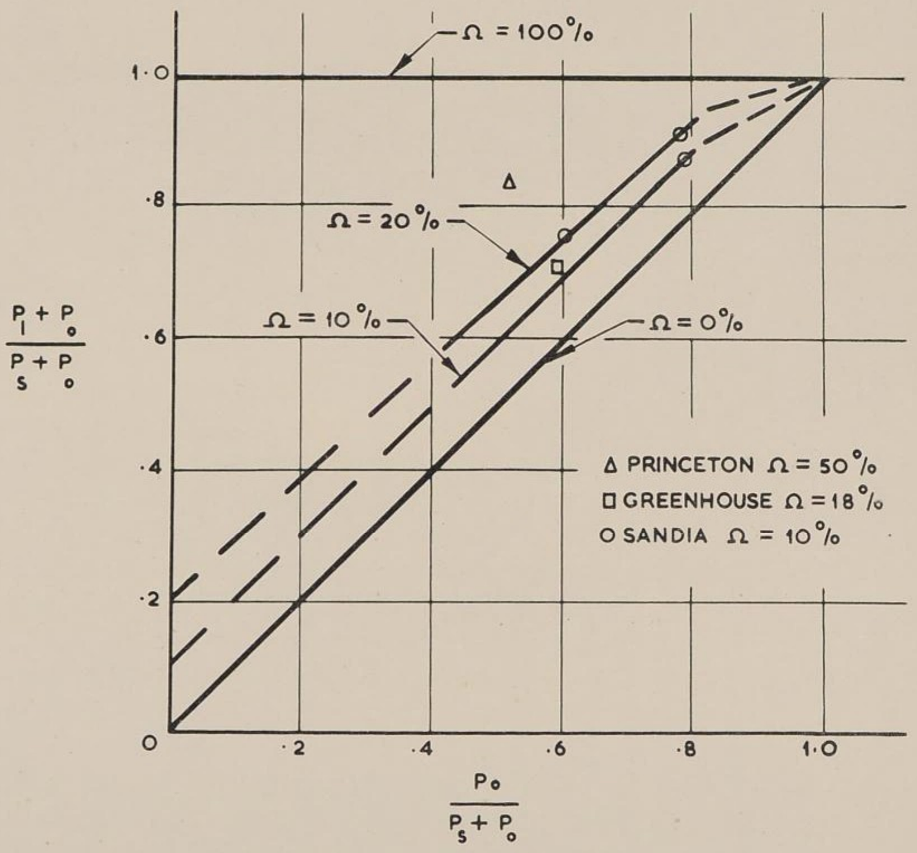
The entering shock wave will be reflected by the opposite wall of the building, increasing the internal pressure. There is also a flow of air through the window openings behind the shock front. The pressure inside the building will eventually be the stagnation pressure of the air flow in the incident blast wave, (approximately, since the process is not strictly isentropic).

A recent model scale study of the mode of collapse of a building in the cases of 17%, 34%, and 100% window areas, is reported in Reference (2).

References

(1) Armour Research Foundation, Project No. M024-1. Report No.18 p.93. (Confidential/Discreet).

(2) A.W.R.E. Report No. E.7/57. (Confidential).



P_I = OVERPRESSURE INSIDE P_o = ATMOSPHERIC PRESSURE

P_s = INCIDENT OVERPRESSURE Ω = PERCENTAGE AREA OF WINDOWS

ENTRY OF BLAST THROUGH WINDOWS.

HEAD – ON INCIDENCE

4.1.2. Delayed Entry due to Panel Breakage

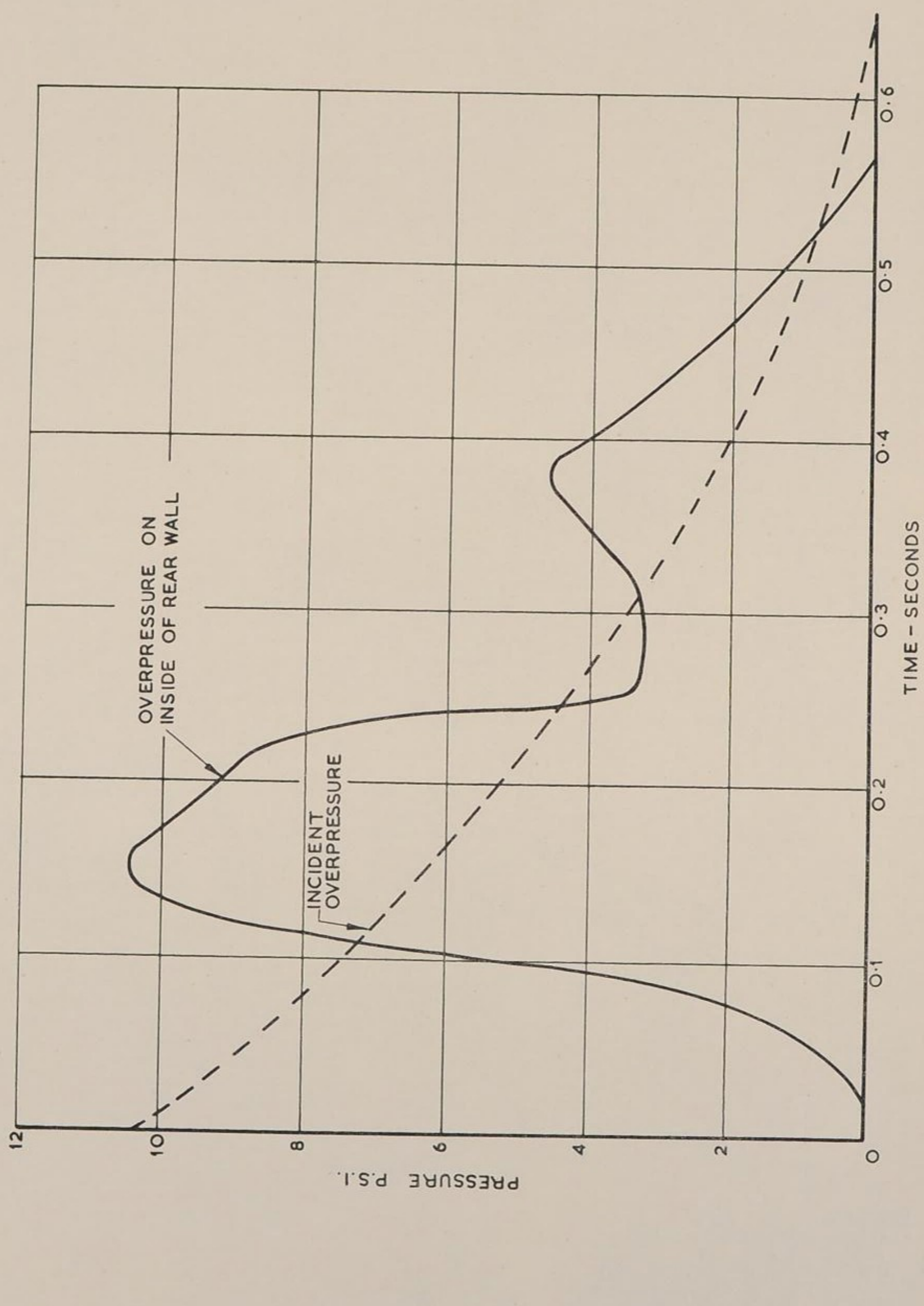
Though windows break practically instantaneously under blast, heavier wall panels, such as brick or reinforced concrete infilling in a frame building, do not. If the failure time is not small in comparison with the time taken by the blast wave to travel the length of the building, the area through which blast may enter gradually increases as the wall panels crack and break up. This results in a steady increase in pressure within the building until the stagnation pressure is reached, and no shock front is formed within the building.

This has been studied in model experiments (1). The model building represented a block of flats 100ft. wide, 40ft. high, and 30ft. deep. The building was divided into compartments 10ft. high and 20ft. wide running the full depth of the building. The front wall of the building was composed of 9in. brickwork panels, represented by a lean lime/sand/cement mortar in the model. Pressure gauges were mounted in the rear wall of each compartment to measure the internal pressure. The model was exposed to the blast from a charge representing an atomic weapon of about 40 KT total yield burst 500 ft. above the ground. The incident over-pressure was 11.3 p.s.i. The failure time of the wall panels would be about 0.05 sec. under these conditions (2), and the incident blast wave would take 0.02 sec. to travel the depth of the building. A typical pressure record is shown in Figure 1; the time zero is taken at the impact of the incident blast wave on the front wall. The main internal pressure rise takes place between 0.07 sec. and 0.15 sec. after impact of the blast wave.

References

(1) A.W.R.E. Report No. E2/55 (Confidential)

(2) A.W.R.E. Report No. E2/53 (Confidential)



ENTRY OF BLAST DUE TO WALL PANEL FAILURE

4.2 Entry through small apertures (the case of surface shelters)

NOTE The following section is relevant only if the occupants of a shelter are protected against violent movement. Otherwise, windage effects generally predominate over those due to overpressure.

If the entrance to a building is small compared with the area of the wall in which it is set, as in the case of a surface shelter, the shock wave entering the building will expand and weaken and the pressure behind it will fall rapidly. The main pressure increase within the building will result from the subsequent flow of air through the doorway, the rate of increase depending on the external pressure, the area of the entrance, and the internal volume into which the air expands. A theoretical treatment of the problem is given in reference (1). The differential equations giving the pressure rise within the shelter cannot be solved in closed form, and the numerical solution is tedious. A number of solutions were obtained using an electronic computer, for certain combinations of forcing pressure, area of doorway, and volume of shelter. The forcing pressure (p_f) is the pressure of stagnant air immediately outside the doorway. It was assumed that the forcing pressure followed a modified Friedlander decay,

$$p_f = 1 + (P_f)_o \left(1 - \frac{t}{\tau}\right) e^{-\frac{2t}{\tau}} \qquad (4.1)$$

where P_f is the initial forcing pressure in atmospheres and τ is the positive duration of the incident blast wave. The solutions cover values for P_f of 0.2, 1, 2, 3 and 4 atmospheres, shelter volumes of 1,500 and 3,000 cubic feet, and entrances of 6, 12 and 24 square feet.

A simpler approximate solution for forcing pressures (P_f) of one atmosphere or more is also given in reference (1). The variation of forcing pressure with time must be known, and in the early stage (up to 20% of the positive duration) it must approximate to an exponential decay. Only the maximum internal pressure and the time at which it occurs are obtained by this method, which is given below.

Starting with the volume of the shelter V (cubic feet), the area of the doorway A (square feet) and the forcing pressure, find P_f and ν by fitting the equation.

$$(p_f)_1 = (1 + P_f) e^{-\frac{t}{\nu}} \qquad (4.2)$$

at the peak and again after one fifth of the positive duration has elapsed.

Then calculate $K = \frac{3566\ A}{V}$ (4.3)

$$\frac{KL}{49} = \frac{0.17725\ A^{3/2}}{V} \qquad (4.4)$$

and $q_1 = K\nu \left[(1 + P_f)^{2/7} - 1 \right]^{\frac{1}{2}}$ (4.5)

Find α by trial to satisfy

$$\alpha^2 - q_1^2 - 2(\alpha - q_1) + 2 \ln \frac{1+\alpha}{1+q_1} = K^2 \nu^2 \qquad (4.6)$$

Then calculate

$$t_1' = \ln \left[\frac{\alpha^2}{-q_1^2 + K^2 \nu^2} \right] \qquad (4.7)$$

$$t_b' = \ln \left[1 - \frac{2}{\alpha} + \frac{2}{\alpha^2} \ln (1 + \alpha) \right] \qquad (4.8)$$

$$t_b = \tfrac{7}{2} \nu (t_b' - t_1') \qquad (4.9)$$

$$(p_f)_{2b} = (1 + P_f) e^{\frac{-t_b}{\nu}} \qquad (4.10)$$

Finally derive $(p_f)_{3b}$ from

$$(p_f)_{3b}^{\frac{1}{7}} - (p_f)_{2b}^{\frac{1}{7}} = \frac{KL}{49} \left\{ \frac{(1 + P_f)^{\frac{1}{7}} - 1}{\left[(p_f)_{2b}^{1/7}\right]^{1/7} - 1} \right\} \qquad (4.11)$$

$(p_f)_{3b}$ is the maximum internal total pressure in atmospheres and t_b is the time at which the maximum occurs. When this approximate method was compared with the exact solutions the value of t_b was found to be about 10% too low, and so the time of rise calculated from the above equations should be increased by that amount. The pressures however, were confirmed.

The entry of blast into surface shelters has been studied experimentally using small scale models (2, 3, 4). Most of this work was concerned with the Type S.1. (C.D.15) Grade A shelter. This is 17 ft. 6 in. x 15ft. x 7ft. internally with a doorway 6ft. x 2ft. Several different baffle arrangements were studied, including two shelters face to face. The effect of varying the width of the doorway was also investigated, and experiments were performed at incident pressure levels between 5 p.s.i. and 70 p.s.i. The scaled blast wave simulated that from a nuclear weapon of about 40 KT yield exploded 500 feet above the ground. The excess pressure within the shelter was least when the doorway was sideways-on to the blast (by 15-20%). The presence of a baffle of any type reduced the pressure rise within the shelter by about 20%. No arrangement of baffle was more efficient in reducing the pressure rise than the standard design in which the blast wall covers about half the width of the shelter. The relation between the pressure rise within the shelter and the incident peak overpressure is shown in Figure 1. The time of pressure build-up inside the shelter was practically independent of the incident pressure level, and at the higher pressures it was comparable with the positive duration of the blast wave; consequently the external pressure falls considerably in this time and the proportion of the blast pressure entering the shelter is reduced. This would not be the case for explosions in the megaton range, when the internal pressure would be practically equal to the external peak pressure over the whole incident pressure range. At a given incident pressure, the build-up time depends on the size of the doorway, as is shown in Figure 2. Again, if the duration of the blast wave is sufficiently long, practically the full incident overpressure will be experienced

inside the shelter for all sizes of doorway, the only difference being that the oscillations of the internal pressure are more highly damped for small entrances and high overpressures.

An electrical analogue giving the pressure-time variation within a shelter has been produced at A.W.R.E.(5). This was based on experimental and theoretical considerations, and depends on the fact that for air flow out of a vented chamber, the decay of internal pressure is approximately exponential over a wide range of conditions. The analogue circuit gives the maximum pressure within the shelter with an error not exceeding 10% of the incident overpressure. The experiments can be completed in a fraction of the time necessary for a field trial, and owing to the much greater flexibility of the method, the effects of a large number of modifications can be quickly assessed. The apparatus is available at A.W.R.E. for the solution of problems.

References

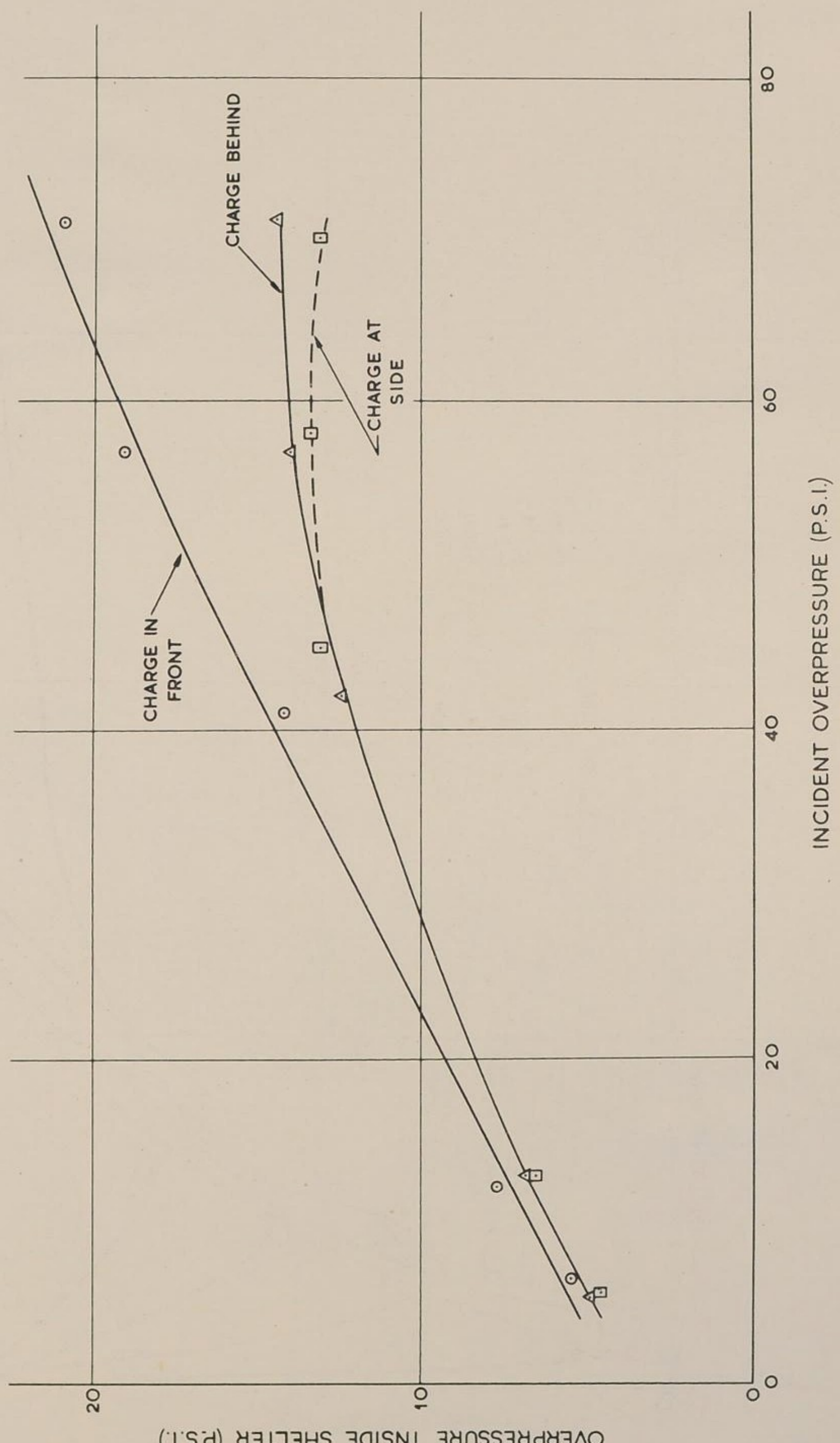
(1) A.W.R.E. Report No. E3/53

(2) Ministry of Supply (H.E.R.) Report No. H22/52

(3) Ministry of Supply (H.E.R.) Report No. H9/53

(4) Ministry of Supply (H.E.R.) Report No. H10/53

(5) A.W.R.E. Report No. 0-16/56



ENTRY OF BLAST INTO A TYPE S.1. SURFACE SHELTER.

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PART III
CHAPTER 4
SECTION 4.2.
FIGURE 2

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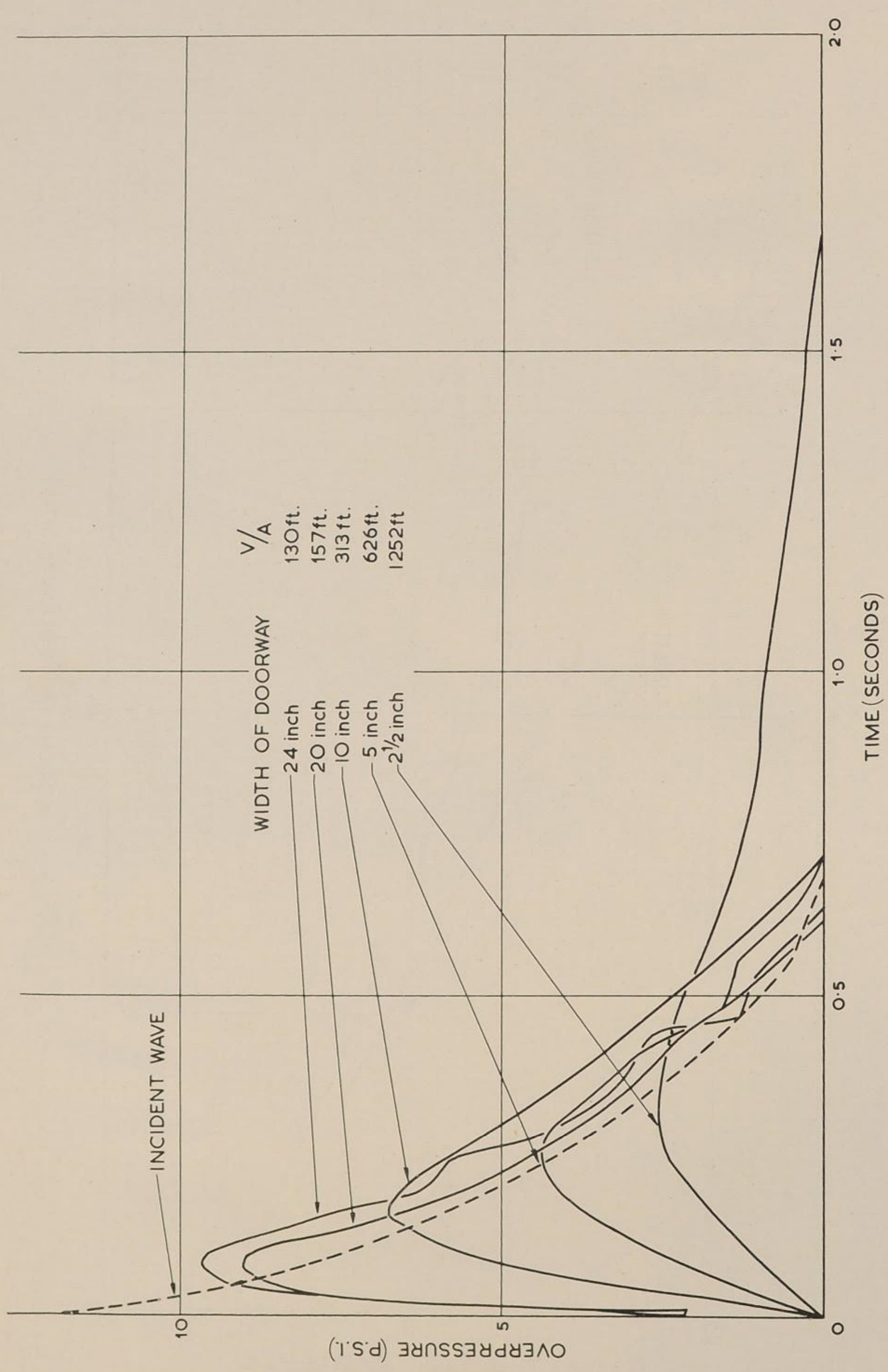
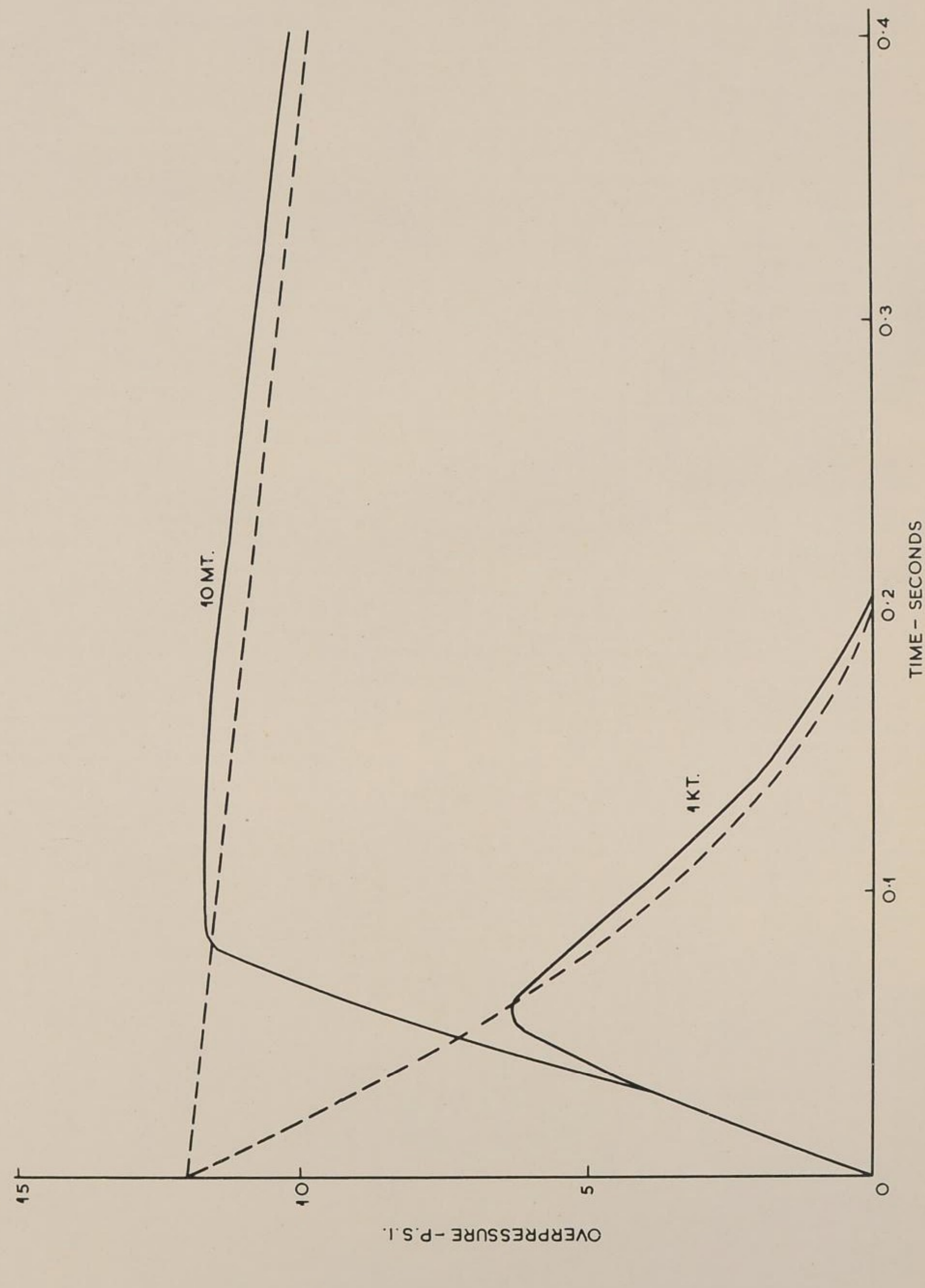


ENTRY OF BLAST INTO SURFACE SHELTERS
WITHOUT BAFFLES

CONFIDENTIAL

Z.15234.R.

D.N.W.
AUG. 1957



ANALOGUE OF TYPE S.1. SURFACE SHELTER.
ENTRY OF BLAST FROM 1 K.T. AND 10 M.T. WEAPONS.

Z.15234.R.

4.3. Open cylinders (tunnels, chimneys, etc.)

Hetherington, Pike and Thornhill (1) have given an approximate mathematical theory for the entry of a long duration blast wave into a pipe or tunnel. When a single shock crosses the open end, as in the case of a tall chimney, or a tunnel entrance in the ground traversed by a Mach wave, they predict that eventually the shock wave travelling down the cylinder will be identical with the incident wave. For a tunnel mouth in the region of regular reflection, they give a table of values of shock strength in the tunnel for incident shock overpressures between 0.2 and 2.0 atmospheres and varying angle of incidence of the incident shock with the ground. They do not consider the attenuation of the shock wave as it is propagated down the tunnel. In practice this attenuation is considerable, but extrapolation back to the mouth of the tunnel gives values of the initial shock strength in reasonable agreement with the theoretical predictions (2,3,4).

The decay of a blast wave after entering a pipe has recently been the subject of experiments at A.W.R.E. (4). The effects of varying the length and diameter of the pipe, the charge weight, and the incident pressure level were investigated. The pipes were horizontal and supported above the ground with the mouth in the region of Mach reflection. Lengths of pipe up to 500 times the diameter were used. For incident shock overpressures between 12 p.s.i. and 70 p.s.i. the pressure decay followed a simple power law

$$\frac{P_x}{P_s} = \left(\frac{x_s}{x_x}\right)^m \qquad (4.12)$$

where P_x is the static overpressure in the pipe at a distance x from ground zero, and P_s is the static overpressure of the incident blast wave at the mouth of the pipe, at a distance x_s from ground zero. The index m is a function of the charge weight and the pipe diameter and for atomic weapons is given by

$$m = 0.705\left(\frac{D}{W^{1/3}}\right)^{-0.322} \qquad (4.13)$$

where D is the diameter of the pipe in feet and W is the yield of the weapon in kilotons.

These equations give values of the overpressure P_x to within 30% of the experimental value. For incident overpressures below 12 p.s.i. the value of m is somewhat less than that given by equation (4.13). At 3 p.s.i. overpressure the reduction is approximately 25%.

When the pipe or tunnel is closed at the far end and its length is small in comparison with that of the blast wave, the reflected shock on returning to the open end causes a rarefaction wave to travel down the tunnel, and this cuts short the duration of the overpressure in the tunnel. A typical record of the pressure at the closed end of a short tunnel is shown in Figure 1.

If the length of the pipe is only a few times its diameter, the diffraction of the shock front into the end of the pipe must be considered in detail, and the orientation of the shock front relative to the pipe will have an important influence on the entry of the blast. The diffraction of blast into ships' funnels has been the subject of

experiments in a shock tube at N.C.R.E. (5). Vertical cylinders of $4\frac{1}{2}$ in. diameter and 5, 10 and 15 in. length were exposed to a vertical shock front. The lower ends were closed and fitted with pressure gauges. The overpressure in the diffracted wave incident on the gauge was obtained from the gauge reading by using equation (2.1.). Only a very slight increase in overpressure was observed with increasing cylinder length. For incident shock overpressures between 4 p.s.i. and 14 p.s.i. the diffracted shock overpressure obeyed the relation

$$P_D = (\tfrac{1}{2} P_s + 1.2) \text{ p.s.i.} \qquad (4.14)$$

References

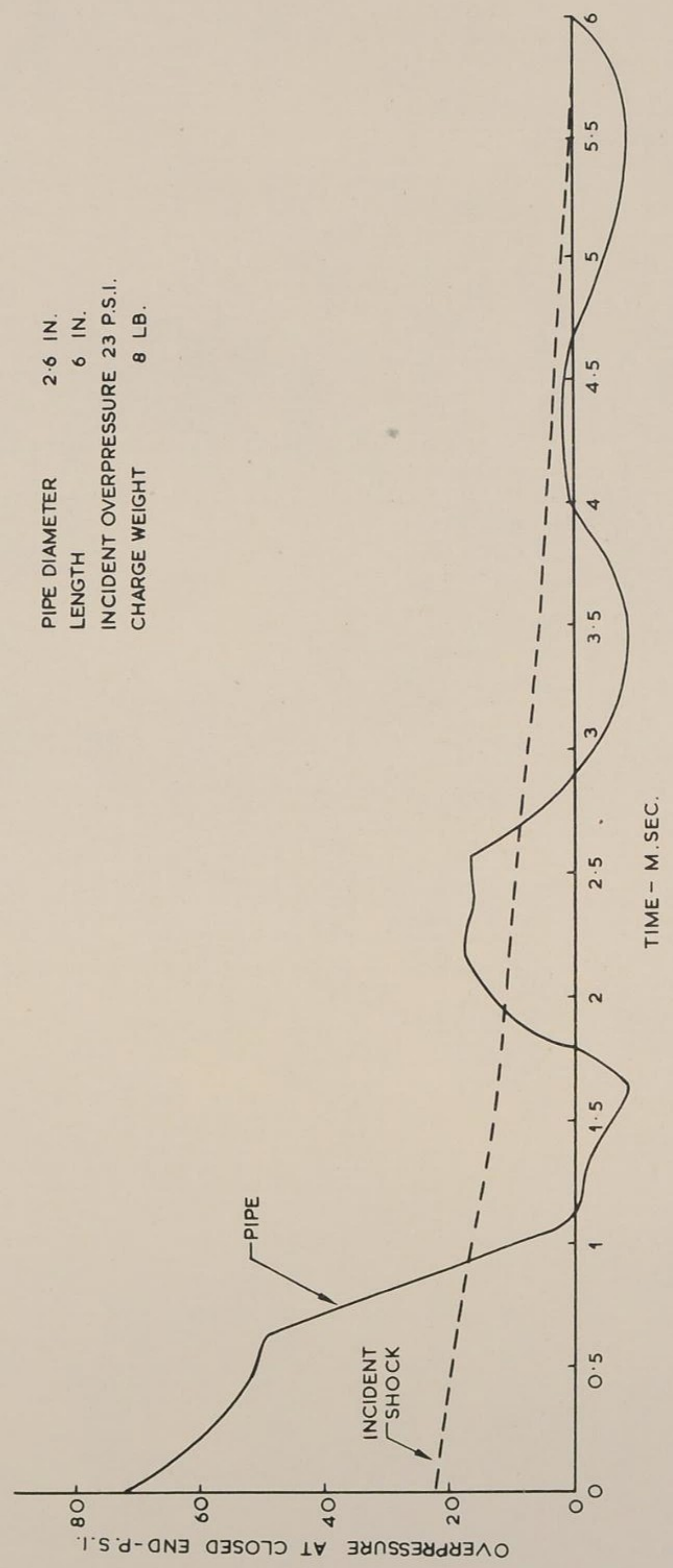
(1) Ministry of Supply (H.E.R.) Report No. H13/53

(2) Ministry of Supply (H.E.R.) Report No. H7/52

(3) Ministry of Supply (H.E.R.) Report No. H15/52

(4) A.W.R.E. Unpublished data

(5) N.C.R.E. Report No. R330.



ENTRY OF BLAST INTO A PIPE.

4.4. Trench

There is very little direct information on the entry of blast into a trench. Reasonable estimates can be made, however from the data on screening of buildings given in section 3. Considering a rectangular slit trench lying at right-angles to the direction of propagation of the blast wave, the average overpressure in the trench will build up to about 150% of the static overpressure in the incident wave due to reflections of the diffracted shock off the walls and floor of the trench. This high pressure will last for about 4 times the time taken by the incident shock to travel the depth of the trench, after which the pressure in the trench should follow the static overpressure in the external blast wave. The gust loading is eliminated.

This estimate was confirmed in a test at A.W.R.E. in which a 1/10th scale model of a standard four-man fire position was exposed to the blast from a small charge (1). Although the equivalent full scale charge weight was only about 32 tons of T.N.T. the duration of the blast wave was sufficiently great to record the diffraction phase of the blast in the trench.

Some further confirmation was obtained at Operation Totem. Collapsible tube gauges on the floor of a circular trench 6 ft. deep and 4 ft. diameter recorded 1.4 times the pressure for the same range at the surface, as measured in the main instrument lane whose bearing from the explosion differed by 70°.

Some description of the nature of damage to field defences will be found in Reference (3), and also in Chapter 9, Section 9.3.2. Reference (4) gives results for Anderson shelters at Operation Hurricane.

References

(1) A.W.R.E. Unpublished data.

(2) A.W.R.E. Report No. T86/54.

(3) A.W.R.E. Report No. T75/54.

(4) A.W.R.E. Report No. T17/54.

CHAPTER 5. RESISTANCE OF STRUCTURES

5.1. Introduction

Even when the forces exerted on a target by air blast are known, the resistance to motion developed by the target must be determined in order to calculate the response of the target to those forces. Most structural targets will be firmly anchored in the ground, and the resistance of the structure to lateral forces will control the response. Military equipment, such as lorries, tanks and aircraft, will however be free to move bodily, and damage will be mainly due to sliding, tipping, tumbling, or impact with other objects.

In the design of structures it is usual to limit the stress in all components to some fraction (the safety factor) of the elastic limit of the construction material. In evaluating the effects of air blast, however, it is necessary to consider the ultimate strength of structures subjected to large irreversible (plastic) deformations. The resistance of structural elements under such conditions will be discussed in this section. There are big gaps in our knowledge of this subject, and most of the information which is available is concerned with slowly applied, or static loads. The static strength of a structure is not in general the same as its short term dynamic resistance. There may be relaxation effects producing rapid creep, and internal damping may make the resistance velocity-dependent.

A detailed and comprehensive treatment of the design of structures to resist atomic blast loading, written from the American structural engineers' point of view, is given by Ammann and Whitney in Reference (1).

References

(1) Ammann and Whitney. Design of Structures to Resist Atomic Blast. 1954. (Confidential)

5.2. Panels

5.2.1 General Remarks A wall panel is a structural element whose thickness is small compared with its lateral dimensions and which is supported at the edges by a comparatively rigid frame, e.g. brick infilling in a reinforced concrete framed building, or a reinforced concrete floor slab supported by steel columns and beams. Wall panels are the means by which the greater part of the blast force is transferred to the main structure of a building. In analysing the response of wall panels to air blast, the edge supports may often be regarded as immovable, as the response time of the supports is usually much longer than the time to panel failure.

The analysis given for metal panels is limited in its application by the need to take account of forces exerted on the framework of the structure as a whole. This is particularly true in the case of all-metal structures, where panel failure is unlikely to occur until the supporting framework has been grossly distorted.

Note added in proof - Attention is drawn to Reference (1).

References

(1) Studies in collapse analysis of rigid-plastic plates with a square yield diagram. E.M. Mansfield
Proc. Roy. Soc. (A). 1226 20th August, 1957, pp 311 - 338

5.2.2. Brick Panels

A theoretical appraisal of the action of brick panels under transverse loads has been made by the Armour Research Foundation (1). Brickwork was assumed to have no tensile resistance, and to behave as a plastic/rigid system, with compression yielding at the plastic hinges. For a panel with one-way support, three plastic hinges would develop, as in Figure 1. The resistive moment would become zero when the central deflection was equal to the thickness of the panel and the panel would collapse.

A number of tests of the transverse loading of brick panels have been made by the Department of Scientific and Industrial Research at the Building Research Station (2, 3, 4) and Road Research Laboratory (2, 5). The test panels comprised $4\frac{1}{2}$ inch, 9 inch and $13\frac{1}{2}$ inch solid brickwork and also 11 inch cavity walls. Either hydraulic or multi-point loading was used to produce a uniformly distributed load. Some panels had window and door openings, others were plain. A number of edge supports were tested, including panels built into steel channel, panels resting against a rigid steel frame, infilling panels in a concrete frame, and support by return masonry walls. Detailed results of these tests are given in References 2, 3, 4 and 5, but to indicate the orders of magnitude involved some typical results are given in Table 5.1.

Table 5.1

Static Transverse loading tests on brick panels

Edge Support	Dimensions (ft.)	Thickness (ins.)	Maximum Pressure (p.s.i.)	Central Deflection At max. (ins)	Central Deflection Final (ins.)	Total Energy absorbed (ton. ins.)
Embedded in channel	$8\frac{1}{2}$ x $8\frac{1}{2}$	$13\frac{1}{2}$	8.2	3.5	-	-
Resting freely against rigid frame	$8\frac{1}{2}$ x $8\frac{1}{2}$	9	3.0	0.12	-	-
9 inch return walls	$8\frac{1}{2}$ x $9\frac{1}{2}$	9	5.25	0.13	-	-
Infilling to concrete frame	11 x 12	11 (cavity)	3.2	2.2	9.5	77
" "	9 x 11	$4\frac{1}{2}$	3.1*	3.0	7.3	39

(* Given as 2.3 p.s.i. in reference (3), taken over total area of frame 11 ft. x 12 ft.)

Walls that are edge-on to the direction of the blast wave will be loaded in shear, and brick infilling may appreciably increase the stiffness of a frame building. In racking load tests on a concrete

encased steel frame at the Building Research Station (6, 7), $4\frac{1}{2}$ inch brick infilling increased the maximum racking load by a factor of 2.45.

There is no direct information on the dynamic resistance of brick panels, but some model tests at A.W.R.E. (8, 9) indicate that it does not differ greatly from the static resistance. In these tests small mortar panels were exposed to the blast from a high explosive charge, and the peak overpressure in the incident wave causing half of the panels to fail was determined. The composition of the mortar was adjusted so that the load/deflection curve for the 1/80th scale panels corresponded correctly to that for 9 inch brick panels tested at the Building Research Station. The peak overpressure for collapse calculated from the static load/deflection curve agreed well with the experimental 50% value.

References

(1) Armour Research Foundation, Report No.18 on Project No. M024-1, (1954) page 376 (Confidential/Discreet)

(2) D.S.I.R. Road Research Laboratory Note No. ARP/30/FGT (March 1940) (Unclassified)

(3) Civil Defence (Interdepartmental) Structural Precautions Research Committee CD/SPR/86 (March 1951) (Secret)

(4) D.S.I.R. Road Research Laboratory Note No. ARP/60/DJM(July 1940) (Unclassified)

(5) D.S.I.R. Building Research Station, Defence Report No.31 (1953) (Restricted)

(6) D.S.I.R. Building Research Station, Report No.2468 (June 1951) (Unclassified)

(7) D.S.I.R. Building Research Station, Defence Report No.34 (1953) (Restricted)

(8) M.O.S. (H.E.R.) Report No. H2/52 (Confidential)

(9) M.O.S. A.W.R.E. Report No. E2/53 (Confidential)

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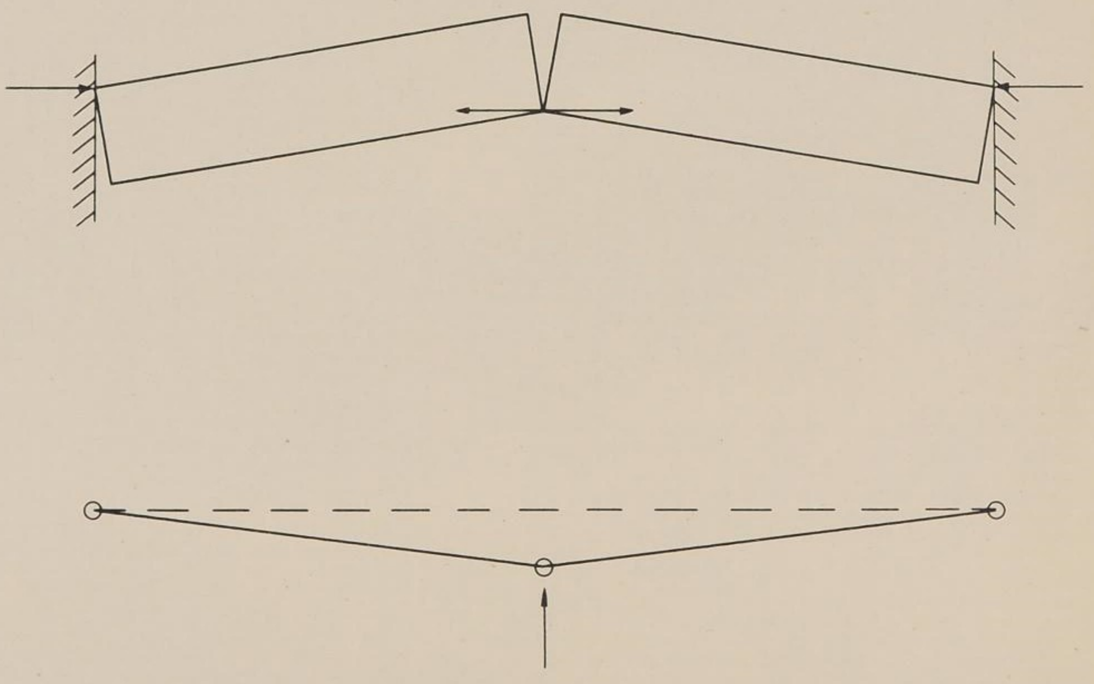

ONE-WAY BRICK SLAB AND EQUIVALENT
PLASTIC-RIGID SYSTEM

Z.15234.R.

5.2.3. Reinforced Concrete Panels

Conventional design methods based on elastic theory are intended to produce structures which are not permanently deformed, damaged, or weakened by the design loads. They give little indication of the actual load/deflection characteristic of reinforced concrete structures. The plastic theory of reinforced concrete design proposed by Whitney (1) gives an approximation to the ultimate static load capacity which agrees well with experimental tests on reinforced concrete beams and slabs in which the percentage of reinforcement by cross-section area is 1% or more. With lower percentages of reinforcement, the tensile strength of the concrete becomes increasingly important. The load at which a panel cracks can be calculated from the modulus of rupture of the concrete, using elastic theory (2) and ignoring the steel The subsequent behaviour on the panel may be determined from Whitney's plastic theory in which the tensile strength of the concrete is ignored. The application of this theory to panels (2-way slabs) is described in Reference (3).

The results of static tests on reinforced concrete panels are summarised in Appendices C and D of Reference (4). The tests at A.W.R.E. referred to there have since been completed and the results are given in detail in References (5) and (6) Most test panels have had low percentages of reinforcement, 0.1% to 1.0% for the most part, and ultimate strengths considerably in excess of those given by the plastic theory have been reported. The Ministry of Works target cubicles in the Monte Bello atomic test of 1952 (5, 7), provide a good illustration of this. The panels were designed by the conventional elastic theory for loads of between 1.7 and 2.1 p.s.i.; the ultimate resistance from Whitney's plastic theory was between 4.4 and 5.5 p.s.i., and static tests on 1/10th scale models gave ultimate strengths between 16.7 and 21.5 p.s.i. The ultimate resistance was therefore ten times the normal design load, and four times the value given by plastic theory.

It is a modern practice (1, 3, 4) to take 1/32nd of the smaller clear span as the maximum central deflection a beam or panel can sustain without failing completely. Ammann and Whitney (11) have used 1/90th of the smaller span as the criterion for avoiding appreciable weakening of the structure. This is a fair figure if the structure is to be usuable after repair, but much larger deflections (up to 1/6th span) have been recorded both in static tests and in field trials with blast loading. Large values of the span-to-depth ratio and percentage reinforcement tend to increase the maximum deflection obtainable.

A typical load/deflection curve for a reinforced concrete panel is shown in Figure 1.

The dynamic behaviour of reinforced concrete panels has been studied in the British atomic weapon trials (5, 7, 8) and in small scale tests in this country (9). This work is continuing, but it is clear that the dynamic resistance is somewhat greater than the static. This seems to be due to viscous damping rather than a straightforward multiplication of the static resistance/deflection characteristic. A constant damping factor of between 0.1 and 0.4 critical, based on the initial slope of the static load/deflection curve, would account for most of the observed results. The apparent damping may be due to a time delay in the onset of plastic yielding in both steel and concrete, the delay time being dependent on the applied load. There is evidence for this in tensile tests on steel and compression tests on concrete, performed in the U.S.A. and summarised in Appendix 4 of Reference (3), and also in flexural tests on concrete in this country (10). Preliminary results for Operation Buffalo are given in Reference (12).

References

(1) Whitney, C.S. Trans. American Soc. Civil Eng. 107, 251 (1942).

(2) Timoshenko, S. "Theory of Plates and Shells", McGraw-Hill, New York (1940).

(3) Whitney, C.S., B.G. Anderson and E. Cohen, J.Amer.Concrete Inst. 26, 589 (1955).

(4) Ministry of Works, Interdepartmental Structural Precautions Advisory Committee, S.P.A. (56) 3, (1956) (Secret)

(5) A.W.R.E. Report No. E-4/55 (Confidential)

(6) A.W.R.E. Report No. E-7/56 (Confidential)

(7) A.W.R.E. Report No. T-66/54 (Confidential)

(8) A.W.R.E. Report No. T-87/54 (Secret)

(9) A.W.R.E. Report No. E-8/56 (Confidential)

(10) Fox, E.N. Cambridge University Engineering Department, Unpublished data.

(11) Ammann and Whitney. Design of structures to resist atomic blast January 1954. (Confidential)

(12) A.W.R.E. Report T6/57 Operation Buffalo. Interim Report Structures Group. (Confidential)

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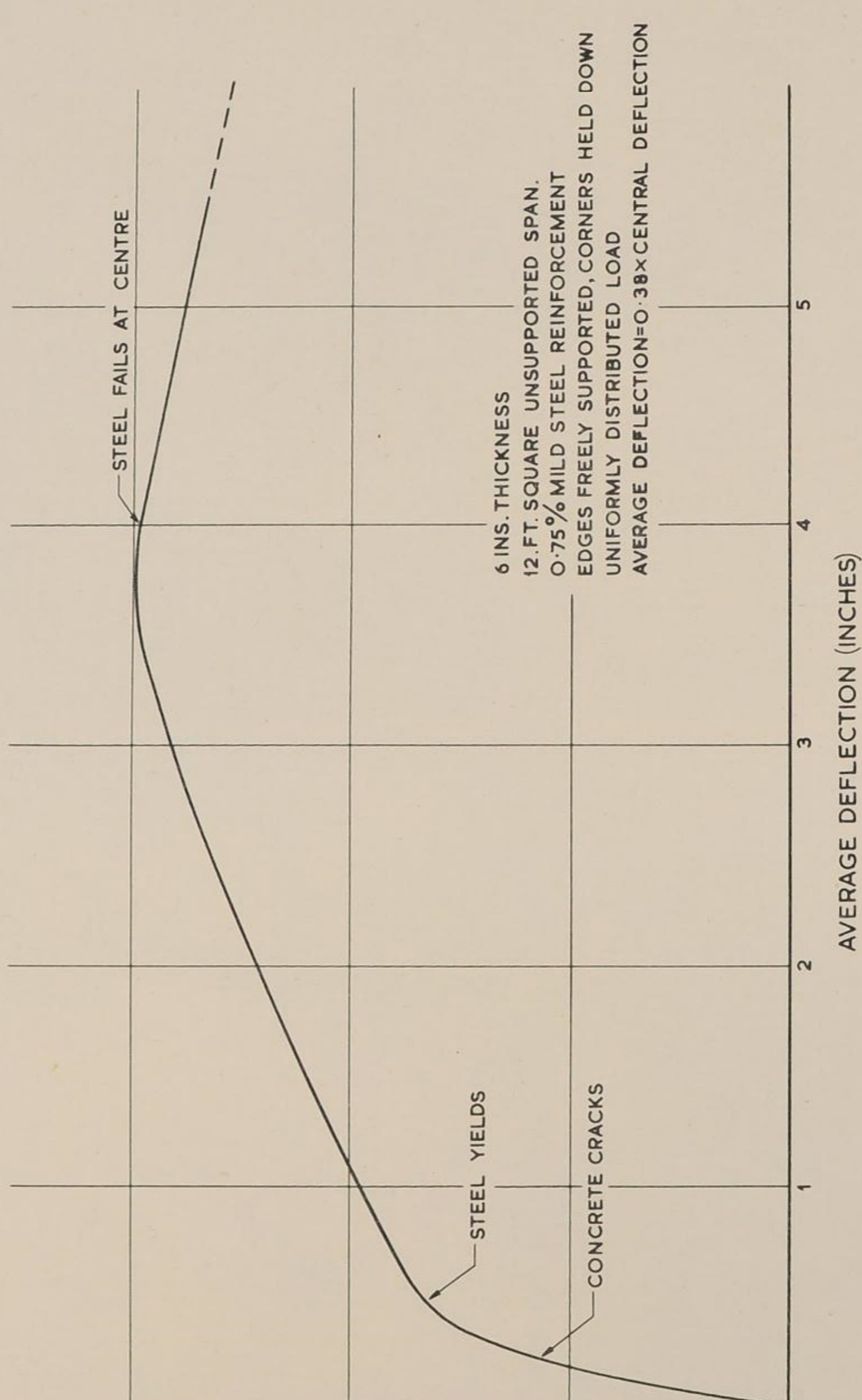
PART III
CHAPTER 5
SECTION 5.2.3.
FIGURE 1



STATIC LOAD/DEFLECTION CURVE FOR REINFORCED CONCRETE PANEL

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5.2.4. Window Glass

It may be assumed that glass under shock remains elastic up to failure. The elastic properties vary with the type of glass and heat treatment, but Kaye and Laby (1) give the following values:-

Young's Modulus $E = 7$ to 10×10^6 p.s.i.

Tensile Strength $T = 4,000$ to $13,000$ p.s.i.

It is recommended that for window glass $E = 8 \times 10^6$ p.s.i., $T=5,000$ p.s.i. should be used.

In an experiment at B.R.L. (2) a number of glazing materials were used to close the end of the 24 inches diameter shock tube. The test windows were 16 inches square and were subjected to the reflection pressure of the shock wave in the tube for a time corresponding to the positive duration of the blast from a 20KT atomic bomb. The incident overpressure at which the windows just failed was determined.

The results are given below:-

Material	Incident Overpressure (p.s.i.)
24 oz (3 mm) window glass	0.75*
44 oz (5.5 mm) window glass	1.0
¼ inch plastic coated glass	1.5
¼ inch safety glass	1.5
¼ inch wire glass	1.0*
¼ inch tempered glass	7.0

~~* Confirmed by recent British trials. Reference (3)~~

The maximum pressure which a window will withstand depends mainly on the maximum stress produced, usually at the edges. It is therefore very dependent on the method of mounting of the glass and on the size of the window. It will, for example, become less as the putty ages and hardens, so that test results with new putty are of uncertain significance. Experience with bangs from supersonic aircraft suggests that practical values as low as 0.1 and 0.01 p.s.i. may be not uncommon, and values down to 0.007 p.s.i. have been observed. Using suitable precautions windows at Foulness are repeatedly subjected to pressure of about 0.1 p.s.i. without harm. The effects of an immediately preceding heat flash are not known. Section 7.1 gives information concerning the velocities of glass fragments.

References

(1) Kaye, G.W.C. and T.H. Laby, "Tables of Physical and Chemical Constants", Eleventh edition, Longmans, London (1956).

(2) Ballistics Research Laboratory Memo. Report No.626 (1952)

(3) A.W.R.E. Report No.T 18/57 (Confidential)

5.2.5. Metal Panels and Plates

Panels of a relatively ductile material, including steels and many aluminium alloys, have very large ultimate loads, due to their ability to resist loads as a membrane, and plastic deformation of 1/10th to 1/5th of the width of the panel may frequently occur before any rupture. In most engineering applications the supporting structure would fail before panel rupture occurs. The ultimate strength of a metal panel depends on the boundary conditions, particularly whether the edges of the panel are held apart by the stiffening and surrounding structures but estimates of the order of magnitude of the ultimate load may be made without particular regard to boundary conditions. Assuming the edges of the panel to be held apart, Greenspon has given the following formula for ultimate pressure of a plastic membrane (Ref.1):

$$p = \frac{w_m}{a} \left(\frac{h\sigma_u}{a}\right) \left\{ 1 + \frac{1}{b^2/a^2} \right\} /0.164 \qquad (1)$$

where w_m = permanent set (out of flatness) at failure

a = width of panel

b = length of panel

h = thickness

σ_u = ultimate stress

In tests on steel diaphragms reported by Greenspon, no failures have occurred until w_m/a has reached at least 0.10, and it is suggested that a conservative estimate of the ultimate load may be obtained from equation (1) with $w_m/a = 0.10$. Further tests are probably required, particularly for other materials such as aluminium alloys.

For comparatively small pressures, the permanent deformation may not exceed that which is frequently built into welded structures during construction, say $w_m/a = 1/150$. to 1/50 Such permanent sets correspond to pressures of the order of 1/10th of the collapse load in equation (1). For these comparatively small permanent sets, both bending and membrane strengths must be allowed for, and Clarkson has given the following approximate formula for the pressure to cause a permanent set of about 1/100th of the plate width ($w_m/a = 1/100$) (Ref.2):

$$p = \frac{k\sigma_s^{\frac{4}{3}}}{E^{\frac{1}{3}}} \left(\frac{t}{a}\right)^{\frac{4}{3}} \qquad (2)$$

where k = 6.5 for square plates or 4.5 for long rectangular plates

σ_s = yield stress

E = Young's Modulus.

If a permanent set $w_m/a = 1/100$ already exists in the structure, the pressure in equation (2) would cause either no increase or only a slight increase in permanent set.

References:

1. Greenspon, J.E. T.M.B. Report 940 (June, 1955).
2. Clarkson, J. Trans. Institution Naval Architects 98, 443 (1956).

5.3 Frames (Beams and Columns)

The resistance/deflection function for steel frames can be computed accurately if the stress/strain relationship for the steel is known. Good summaries of the deflection properties of steel frames have been given by Johnston (1,2), and details of the application of plastic design theory are given in Appendix 3 of Reference (3). An example of the detailed analysis of a particular building frame is given in Reference (4). It should be noted that the ultimate resistance of a frame to lateral distortion is often determined by the shear strength of the rivets at the joints or connections to the foundations.

Considerable increases in the yield strength of steel at high rates of loading have been reported, and in Appendix 4 of Reference (3) it is recommended that an increase of up to 60% should be allowed in designing blast resistant construction. Johnston however, questions the validity of this (2). He considers the deflection of wide flange beams in the frame of a building subjected to blast loading, and concludes that the dynamic increase in yield strength would not exceed 10 to 15%. He compares this with the variations in strength from more than 3,000 mill control tests, which gave a coefficient of variation of approximately 7.5%, and concludes that no blanket increase should be used in applying static test data to dynamic analysis. However, it has been stated (3), although detailed results are not available, that deflections calculated by ultimate design methods, including a dynamic increase factor, agree well with those observed in a U.S. atomic bomb trial. The maximum deflections at roof level of two window-less three-storey buildings, one framed in steel and the other in concrete, were within 20% of the design values. Preliminary information on the behaviour of steel frames from British trials is given in reference (5).

References

(1) Johnston, B.G. "Steel Frames for Industrial Buildings", M.I.T. Conference on "Building in the Atomic Age". (June, 1952).

(2) Johnston, B.G. "Structural Steel Members and Frames" Proceedings of the Symposium on "Earthquake and Blast Effects on Structures" University of California, (June, 1952).

(3) Whitney, C.S., B.G. Anderson and E. Cohen, J. Amer. Concrete Inst. 26, 589 (1955).

(4) Armour Research Foundation, Report No. 18 on Project No. M.024-1, page 217 (1954). (Confidential/Discreet)

(5) Operation Buffalo, Interim Report Structures Group. I.Ll. Davies A.W.R.E. Report No. T6/57. (Confidential).

5.4 Buildings with Load-Bearing Walls

The lateral resistance of brick construction with load-bearing walls is rather poor. The main part of the resistance is due to shear forces in the side walls and transverse partitions. Tests have shown that a vertical dead load increases the lateral resistance of brickwork (1,2) but in practice the reaction at the edges may not be sufficient to develop the full panel strength.

Only one determination of the transverse strength of a building with load-bearing walls hae been recorded (3). This was an experiment conducted at A.W.R.E. when a two storey farmhouse had to be demolished. A distributed horizontal load was applied to the front elevation (walls and roof) of the house by means of jacks, cables and load-spreaders. The horizontal deflection of each of the nineteen loading points was measured up to collapse, which occurred at an average deflection of 17 inches. The maximum horizontal load taken by the house was 50 tons, equivalent to an average distributed pressure of 0.75 p.s.i. The total energy absorbed up to collapse was 49.3 foot tons. The load/deflection curve for the house is shown in Figure 1. The house was built in 1926, the exterior walls were $11\frac{1}{2}$ inch cavity brickwork in local London stock bricks, and the total weight of the house was 120 tons.

A method of calculating the resistance/deflection function for masonry walls loaded in shear is given in Appendix 3 of Reference (4).

References

(1) Building Research Board. Special Report No.3 - "Report of a Research on the Strength of Thin Walls" by Dr. O. Faber, H.M.S.O. (1921).

(2) D.S.I.R. Road Research Laboratory Note No. ARP/30/FGT (Unclassified)

(3) Ministry of Supply (H.E.R.) Report No. H3/51 (Restricted)

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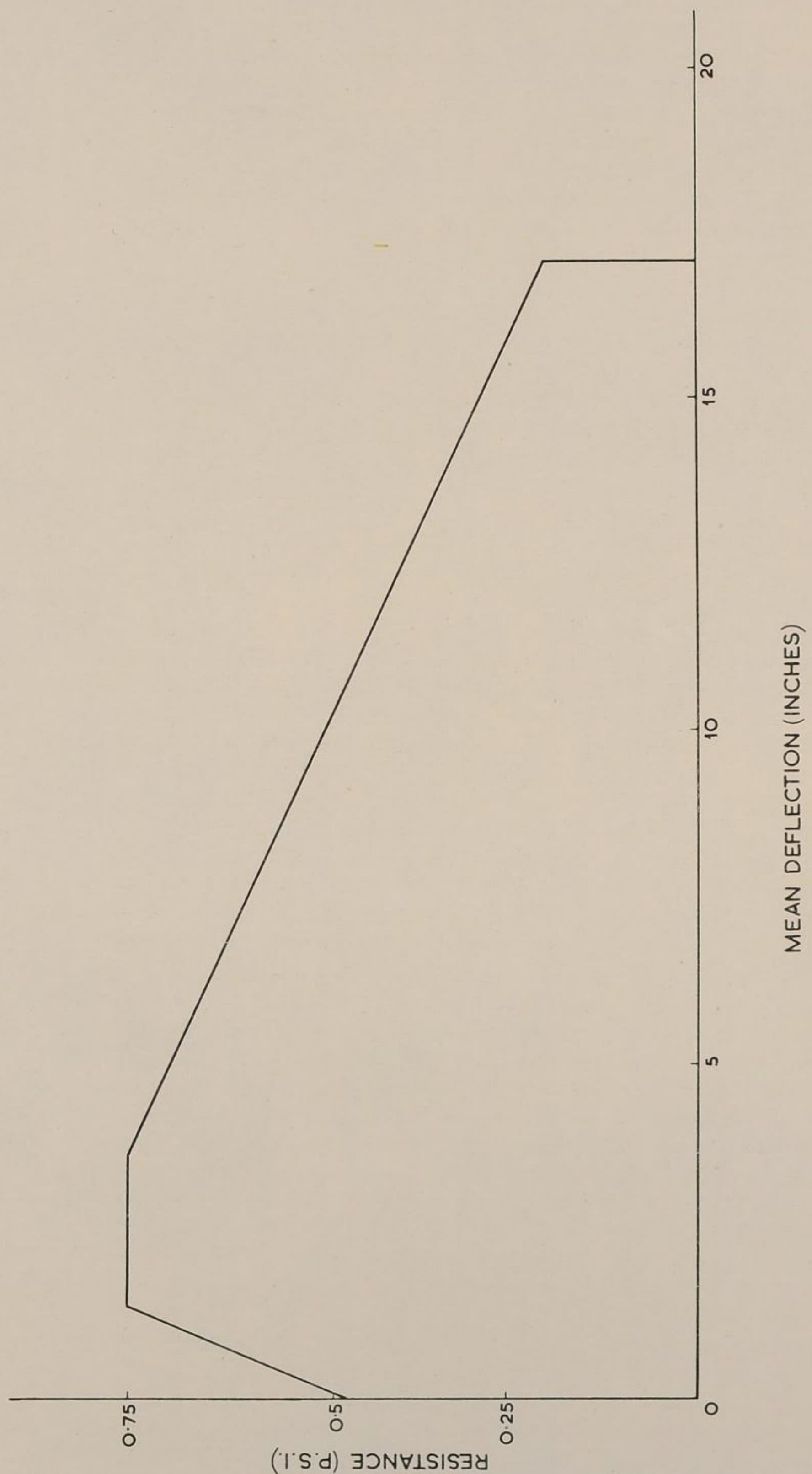


RESISTANCE / DEFLECTION CURVE FOR HOUSE WITH LOAD-BEARING WALLS

CONFIDENTIAL

CHAPTER 6 - ANALYSIS OF DEFORMATION

6.1. Sequence of Calculations

When calculating the deflections of a target subject to blast forces, the way in which the load is transferred from one part of the structure to another must be considered together with the development of reactions resisting the motion. Consider as an example, a frame building with wall panels. The blast pressure acts on the wall panels and they begin to move. Internal stresses are set up as the panel deflects, producing a reaction which is applied to the frame at the edges of the panel. The force acting on the frame is the resistance to motion of the panel, and not the blast pressure itself. If the blast pressure is sufficiently high the wall panel will burst after a certain time, which can be calculated, and the forces acting on the frame will then be those due to the drag of the blast wind. Highly resistant wall panels will therefore transfer a much greater load to the frame than will weak ones. The frame in turn transfers its load to the foundations of the building.

For targets which are not anchored to the ground, such as vehicles, the only resistance to motion will be due to friction, and damage will be caused mainly by overturning or impact with other objects. In such cases the maximum velocity attained will determine the degree of damage.

To calculate the deflection (x) of a target or component as a function of time (t), one must first determine the force applied to the target by the blast wave, as described in Sections 1 to 4 above. The blast force is determined as a function of time and may be written P (t). The resistance (R) of the target must then be found, as in Section 5 above. This is a function of displacement and, if damping is considered, of velocity, $R(x,\dot{x})$. One then has to solve the equation of motion

$$M \ddot{x} + R(x, \dot{x}) = P(t) \qquad (6.1)$$

In a multi-component system R will depend on the displacements of all the other components, but a single degree of freedom approximation is often sufficiently accurate. For example, when considering the motion of a wall or roof panel, the main structure of the building may be assumed to be rigid as most of the mass is concentrated in the frame and floors, and the reaction time of the panel will be small compared with that of the whole structure. Having obtained a solution for the panel, its reaction on the main structure is known as a function of time, and may be used to calculate the motion of the structure. It has been found that a building frame of normal design can be treated as a one degree of freedom system, nearly all the lateral distortion appearing in the ground floor columns (1,2).

The simplified system represented by equation (6.1) must be dynamically equivalent to the actual target. This may be achieved either by identifying x with the deflection of a particular point of the target, such as the centre of a beam, and multiplying the mass by an "equivalent mass factor", or by making x the average deflection of all points on the target. The former method is usually adopted by American workers, but the latter seems more logical, if the average deflection can be determined. The ratio of average to central deflection has been measured at A.W.R.E. for the uniformly distributed loading of small rectangular plaster panels with a length to breadth ratio of 2 : 1 (3) and also of square concrete panels (4). In both cases the ratio was found to be close to 0.38 from zero deflection to near-collapse. In order to solve equation (6.1) the resistance function

$R(x,\dot{x})$ must be expressed in a simple form. For most applications we can write

$$R(x,\dot{x}) = F(x) + b\dot{x} \qquad (6.2)$$

where $F(x)$ is the static load/deflection function and b is a constant damping coefficient. The equation of motion then becomes

$$M\ddot{x} + b\dot{x} + F(x) = P(t) \qquad (6.3)$$

Methods of solving this equation are given in Section 6.2 below.

References

(1) Armour Research Foundation Report No.18 of Project M024-1 (1954) (Confidential/Discreet)

(2) Jacobsen, L.K. "Dynamic Behaviour of Simplified Structures up to the Point of Collapse" "Proceedings of Symposium on Earthquake and Blast Effects on Structures" - University of California (June, 1952) ~~(Confidential).~~

(3) A.W.R.E. Foulness Laboratory Note 1/54 (Confidential)

(4) A.W.R.E. Report No. E-4/55 (Confidential)

6.2 Methods of Solution

The basic equation of motion to be solved is

$$M\ddot{x} + b\dot{x} + F(x) = P(t) \qquad (6.3)$$

where F(x) and P(t) are either experimentally or empirically determined functions. We can obtain an approximate step-by-step solution to (6.3) either by direct numerical integration or by a semi-graphical (phase-plane) method, or we can approximate F(x) and P(t) by simple analytical functions and obtain an exact solution of the resulting equation. The last method involves the most work, but once the solution has been obtained in general terms it may be expressed graphically and applied to a large class of problems. The three methods of solution will be described in turn.

6.2.1. Numerical Integration

Equation (6.3) is re-written as

$$\ddot{x} = \frac{1}{M}\left[P(t) - F(x)\right] - \frac{b}{M}\dot{x} \qquad (6.4)$$

integrating over the interval t this becomes

$$\Delta\dot{x} = \left[\frac{1}{M}\left\{\overline{P(t)} - \overline{F(x)}\right\} - \frac{b}{M}\frac{\Delta x}{\Delta t}\right]\Delta t \qquad (6.5)$$

where $\overline{P(t)}$, $\overline{F(x)}$, are the average values of P(t) and F(x) in the interval Δt. In order to obtain the change in displacement Δx we assume the acceleration is constant during the interval Δt. The average velocity in the interval is then

$$\overline{\dot{x}} = \dot{x} + \tfrac{1}{2}\Delta\dot{x} \quad \text{and} \qquad (6.6)$$

$$\Delta x = \overline{\dot{x}}\,\Delta t \qquad (6.7)$$

As F(x) depends on Δx, and both appear in equation (6.5) for $\Delta\dot{x}$, it is necessary to assume a trial value for Δx, insert this in equation (6.5) and calculate Δx from equations (6.6) and (6.7). The assumed and calculated values of Δx are then compared, and if they do not agree a new trial value is assumed and the calculation repeated. The size of the interval Δt will depend on the rate of change of F(x) and P(t), and the interval may be varied as the calculation proceeds. Initially the interval should be about $\frac{1}{8}$th of the period of vibration of the structure, so that the first maximum displacement is reached in four or five steps. Some times to failure are given in Table 6.1 quoted from Reference (1).

An example of the method of tabulating the calculations is given in Table 6.2 below for the reinforced concrete panel whose static load/deflection curve is given in Figure 1(Section 5.2.3). It is a square panel with a clear span of 12 ft. and thickness 6 ins. It is assumed to form the roof slab of an underground structure, the roof having no earth cover. The incident blast wave is from a 5 kiloton explosion at a peak overpressure of 13 p.s.i. Taking a concrete density of 150 lb./cu.ft. and a damping coefficient 0.125 of the critical value for small deflections, the equation of motion (6.4) becomes

$$\ddot{x} = 738.5\left[P(t)-F(x)\right] - 37.5\,\dot{x} \qquad (6.8)$$

where P(t) and F(x) are in p.s.i. x in inches and time in seconds.

TABLE 6.1

Time Required for Failure of Panels (Nominal Weapon Front Wall (Seconds)

Panel	3 p.s.i.	5 p.s.i.	8 p.s.i.
Corrugated Asbestos	0.0048	0.0032	0.0019
Steel Deck	0.0136	0.0085	0.0064
Reinforced Concrete	No failure	0.09	0.04

(d) The wearing of a steel helmet with the strap under the chin is likely to lead to neck injury if the wearer is struck by a blast wave of peak static overpressure greater than 4 p.s.i.

References

(1) Krohn P.L. and J. McGregor, A.W.R.E. Report T3/58 "The Physiological Effects of Long Duration Blast Waves." (Confidential)

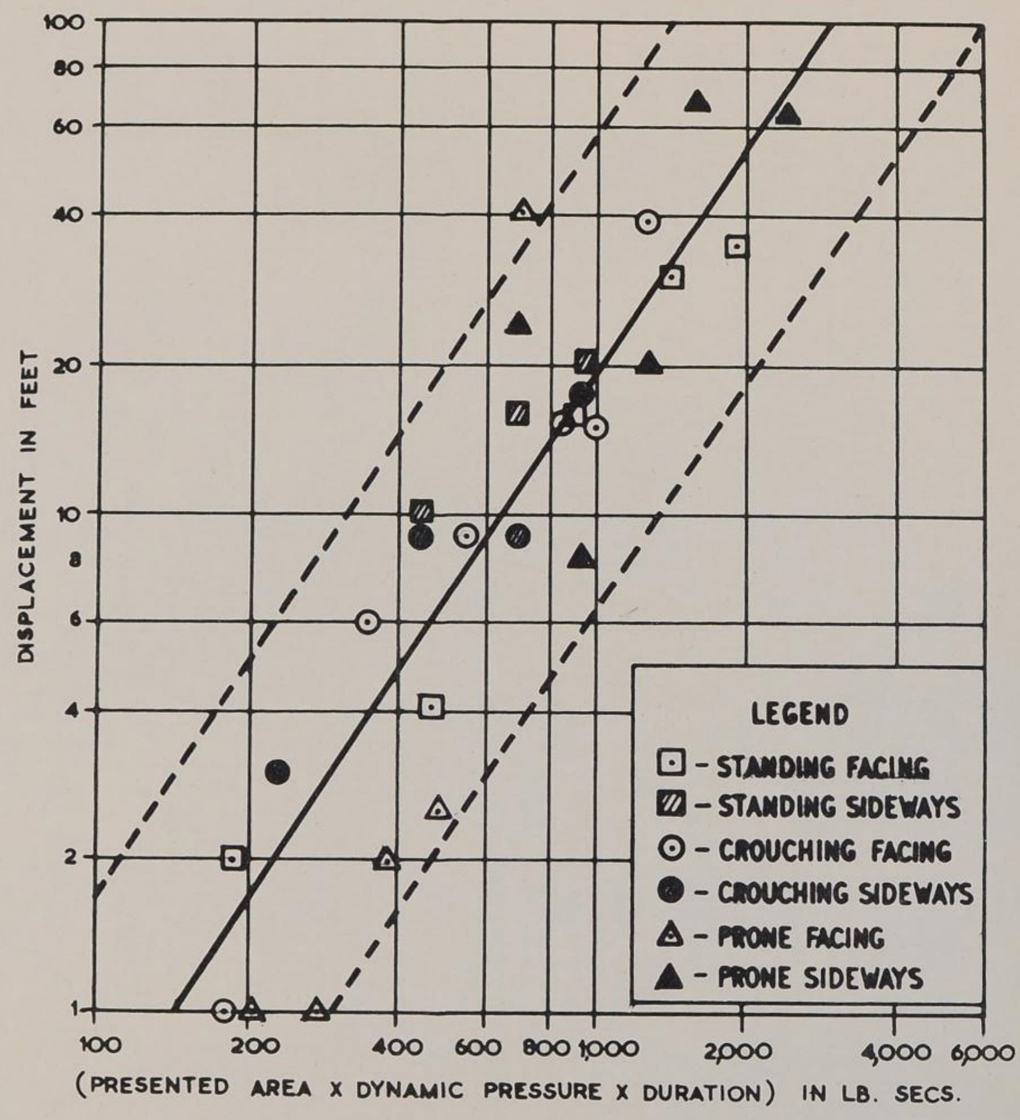
(2) Butterfield, W.J.H., E.G. Hardy and E.R. Drake Seager, A.W.R.E. Report T2/59. "The Effects of Blast on Dummy Men Exposed in the Open" (Confidential)

(3) Liston, R.H.A. A.R.E. Report 1/48, Part 6. "The Kinematic Effect of Blast on a Man in the Open."

(4) Lovell, G., R.A.E. Technical Note Mech.Eng. No.176 (May, 1954).

(5) Latham, F., "Linear Deceleration Studies and Human Tolerance", Clinical Science, 17, 121(1958).

(6) Martin, A.R.F., A.W.R.E. Report T6/59, "The Effects of Blast on Dummies and Scout Cars." (Confidential)



THE RELATIONSHIP BETWEEN DISPLACEMENT AND (AREA PRESENTED X DYNAMIC PRESSURE X DURATION)

CHAPTER 9 - EMPIRICAL DATA FOR SELECTED TARGETS

9.1 Introduction

9.1.1 Sources and nature of data.

The object of this section is to provide, in as convenient a form as possible, the best available estimates of the range at which a given probability of a defined degree of damage is to be expected for different types of target, as a function of the yield of the weapon. The data are limited to primary damage by blast and include the loading effects of Mach and regular reflection, but neglect any secondary effects, such as may be caused by fires initiated by electrical short circuits, by ruptured gas mains or by over-turned stoves or furnaces. Except where otherwise stated, a random target orientation is assumed. The data summarise American operational and trials experience up to June 1955(1) together with some data from British trials up to the end of 1956. In the former case some additional data has been derived from theoretical extrapolations. Where present data does not justify fine distinctions, targets have been presented in groups having similar damage criteria. No attempt is made to define the precise extent and location of the damage to an individual target but conditions corresponding to severe, moderate and light levels of damage are given in general terms for each class of target. It is assumed that the targets in question are situated in isolation on effectively flat average ground, so that the effects of irregularities of terrain, or screening or reflection of blast by adjacent structures, may be neglected. If precursor conditions exist, damage distances for pressure sensitive targets are reduced, when pressures greater than 8 p.s.i. are involved. The reduction in a particular case can be found by inter-comparison of the ranges for a given overpressure under precursor and non-precursor conditions. [M.E.A.W. Chapter 1.] Until more definite information is available concerning drag targets, it is recommended that no modification should be made to the damage curves to allow for precursors in such cases.

9.1.2. Distinction between pressure and drag targets.

Although most real targets have very complicated responses to air blast it is convenient to make a broad distinction between pressure sensitive targets which are mainly damaged by the static overpressure of the blast wave, and drag sensitive targets which are sensitive mainly to the drag forces caused by the velocity of the airstream which accompanies the blast wave. Under each of these headings it is possible to group a fair number of targets, each group exhibiting a wide range in blast resistance. Table I may be used to determine the appropriate damage criteria for the targets covered by this section. The nature of the various types of blast loading has been discussed in detail in the earlier chapters of this part of the Manual.

9.1.3. Types of damage curves

The data are presented mainly in three types of graph. In a few cases (Section 9.2.1 figs.1.2) a simplified presentation is used to show directly the relationship between severe damage distance and yield, for a variety of types of structure, in the case of low burst heights. Secondly, in the case of structures whose damage mechanism may change appreciably under different conditions, the relation between distance from ground zero for a given damage level and actual height of

(1) Capabilities of Atomic Weapons. A.F.S.W.P. June 1955 U.S. Dept. of the Army Manual TM 23-200. (Secret-Atomic)

burst is shown for a range of actual yields. The third type of graph shows the relationship between the scaled distance of damage and scaled height of burst for various probabilities of various degrees of damage by a 1 KT weapon. This is called an iso-damage curve, the method of construction of which has been discussed in Chapter 6, Section 6.3, above. Unless otherwise stated, these curves require scaling with $W^{\frac{1}{3}}$ for height of burst and $W^{0.4}$ for damage distance.

9.1.4 Definitions of Damage Levels.

The definitions of severe, moderate and light damage naturally vary in detail from one class of target to another and are therefore given in association with the appropriate curves. The following may be taken as a general guide to American practice as used in this chapter:

Severe Damage. That degree of damage which precludes further use of the target in question for the purpose for which it is intended without essentially complete reconstruction. Extensive repair will be needed before use for any purpose.

Moderate Damage That degree of damage which precludes effective use of the target for the purpose for which it is intended until major repairs are made.

Light Damage That damage which does not prevent continued operational use of the equipment or target. Can usually be repaired locally.

British System of House Damage Classification

As there is no simple relationship between the American system of damage definition as used in this chapter, and the current British system, which was developed for use during the last war, the British system is quoted for purposes of inter-comparison.

The following definitions apply to estimates of damage to typical British brick-built houses with 9" solid brick walls or 11" cavity brick walls.

Category A Damage

Houses completely demolished, i.e. over 75% of the external brickwork demolished.

Category B Damage

Houses so badly damaged as to be beyond repair and must be demolished as soon as opportunity arises.

House property is included in this category if 50 - 75% of the external brickwork is destroyed or, in the case of less severe destruction, if the remaining walls have gaping cracks rendering them unsafe.

Category C_b Damage

Houses which are rendered uninhabitable by serious damage and need repairs so extensive that they must be postponed until after the war. Examples of damage resulting in such conditions include partial or total collapse of roof structures, partial demolition of one or two external walls, up to 25% of the whole, and severe damage to load-bearing partitions necessitating demolition and replacement.

Category C_a Damage

Houses that are rendered uninhabitable but that can be repaired reasonably quickly under war-time conditions. The damage sustained not exceeding minor strut damage and partitions and joinery wrenched from fixings.

Category D Damage

Houses requiring repairs to remedy serious inconveniences, but remaining inhabitable. Houses in this category may have sustained damage to ceilings and tiling, battens, and roof covering, and minor fragmentation effects on walls and window glazing. Cases in which the only damage amounts to broken glass in less than 10% of the windows are not included.

9.1.5 Other damage levels and probabilities of damage

The majority of the curves are presented on the basis of a 50 per cent. probability of severe damage. In some cases sufficient data is available to justify the insertion of curves for other probabilities and other damage levels. Where this is not possible an approximate estimate may be obtained in the following way:-

90 per cent. probability of severe damage. Use a curve appropriate to a weapon of half the actual yield at the same height of burst.

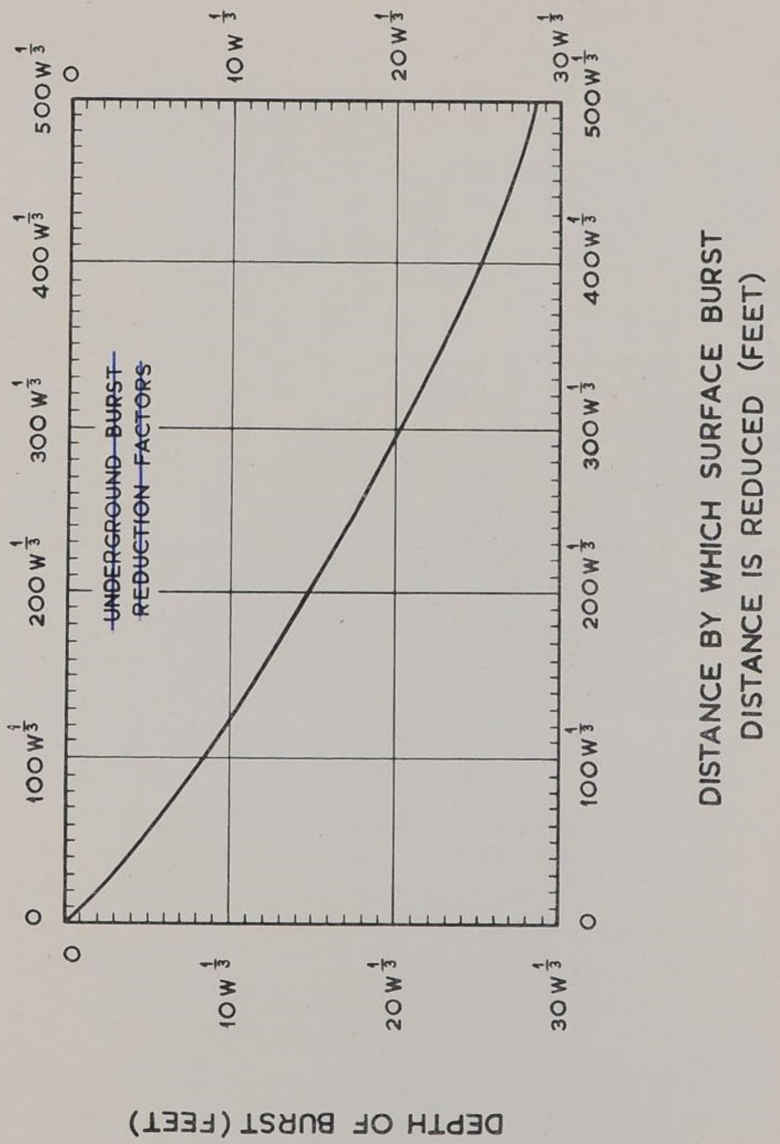
10 per cent. probability of severe damage. Use a curve appropriate to a weapon of twice the actual yield at the same height of burst.

50 per cent. probability of moderate damage. Use a curve appropriate to a weapon of four times the actual yield.

50 per cent. probability of light damage. The 1 p.s.i. blast wave overpressure contour may be used to represent light damage to most targets. Exceptions to this, such as bridges or blast resistant structures, are specifically annotated.

9.1.6 Air blast damage from underground bursts.

In the case of relatively shallow underground bursts, air blast causes severe damage to most surface structures at ranges less than those for a corresponding air burst, but such that damage from cratering and ground shock is insignificant. For depths of burst less than $35W^{1/3}$ feet the damage distance is first found for a surface burst and is then reduced by the amount given in Figure 1 for the scaled depth of burst.



DAMAGE RADIUS REDUCTIONS FOR UNDERGROUND BURSTS.
SEVERE DAMAGE

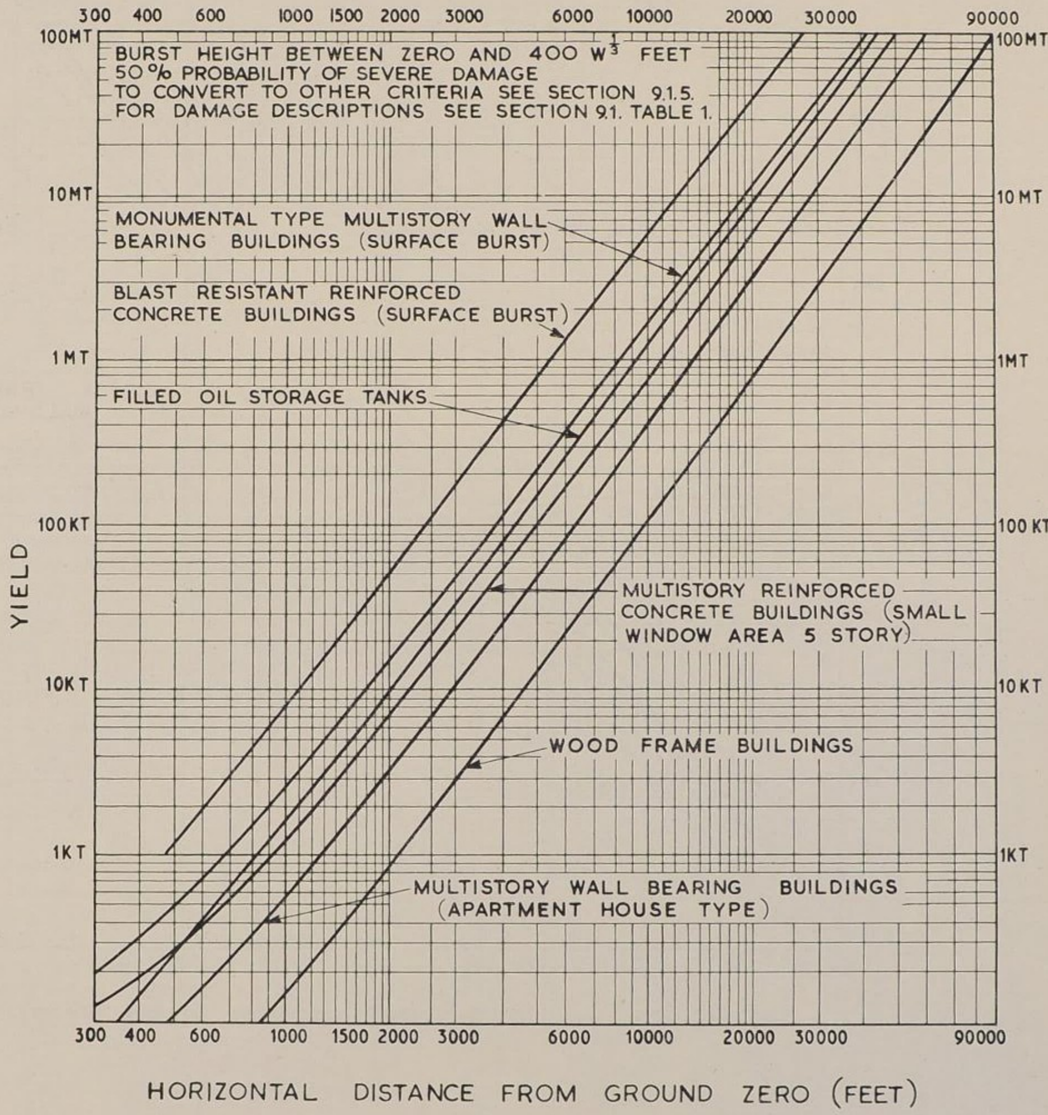
TABLE I - Damage to Structural Types Primarily Affected by Blast Wave Overpressure during the Diffraction Process

Section	Fig.No.	Description of Structure	Description of Damage: Severe	Moderate	Light
9.2.2.	1	Multistory reinforced concrete building with reinforced concrete walls, blast resistant designed, no windows, three storey.	Walls shattered, severe frame distortion, incipient collapse of first floor columns.	Walls cracked building slightly distorted, entranceways damaged, doors blown in or jammed. Some spalling of concrete.	
9.2.2.	2	Multistory reinforced concrete building with concrete walls, small window area, five storey.	Walls shattered, severe frame distortion, incipient collapse of first floor columns.	Exterior walls badly cracked. Interior partitions badly cracked or blown down. Structural frame permanently distorted; spalling of concrete.	Windows and doors blown in. Interior partitions cracked.
9.2.3.	1	Multistory reinforced concrete frame office type building five storey. Light weight low strength walls fail quickly.	Severe frame distortion. Incipient collapse of lower floor columns.	Frame distorted moderately. Interior partitions blown down. Some spalling of concrete.	Windows and doors blown in. Light siding ripped off. Interior partitions cracked.
9.2.4.	1	Multistory steel frame office type building, five storey. Light weight low strength walls fail quickly.	Severe frame distortion. Incipient collapse of lower floor columns.	Frame distorted moderately. Interior partitions blown down.	Windows and doors blown in. Light siding ripped off. Interior partitions cracked.
9.2.5.	1	Heavy steel frame industrial building, single storey, with 50 ton crane capacity. Light weight low strength walls fail quickly.	Severe distortion of frame (½ column height deflection).	Some distortion of frame; cranes, if any, not operable until repairs made.	Windows and doors blown in. Light siding ripped off.
9.2.5.	2	Medium steel frame industrial building, single storey, with 20 ton crane capacity. Light weight low strength walls fail quickly.	Severe distortion of frame (½ column height deflection).	Some distortion of frame; cranes, if any, not operable until repairs made.	Windows and doors blown in. Light siding ripped off.
9.2.5.	3	Light steel frame industrial building, single storey, with up to 5 ton crane capacity. Light weight low strength walls fail quickly.	Severe distortion of frame (½ column height deflection).	Some distortion of frame; cranes, if any, not operable until repairs made.	Windows and doors blown in. Light siding ripped off.
9.2.6.	1	Multistory wall bearing building, monumental type four storey.	Bearing walls collapse resulting in collapse of structure supported by these walls. Some bearing walls may be shielded enough by intervening walls so part of structure may receive only moderate damage.	Exterior walls facing blast badly cracked, interior partitions badly cracked, although toward far end of building damage may be reduced.	Windows and doors blown in. Interior partitions cracked.
9.2.6.	2	Multistory wall bearing building, brick apartment house type, up to three storey.	Bearing walls collapse resulting in total collapse of structure.	Exterior walls badly cracked, interior partitions badly cracked or blown down.	Windows and doors blown in. Interior partitions cracked.
9.2.7.	1	Wooden frame building, house type, one or two stories.	Frame shattered so that structure is for the most part collapsed.	Wall framing cracked. Roof badly damaged. Interior partitions blown down.	Windows and doors blown in. Interior partitions cracked.
9.2.8.	2	Highway and railroad truss bridges, spans of 150ft. to 250ft. (See figure title for effects of orientation.)	Total failure of lateral bracing, collapse of bridge.	Some failure of lateral bracing such that bridge capacity is reduced about 50%	Capacity of bridge unchanged. Slight distortion of some bridge components (use Q - 0.6 psi curve scaled to weapon yield.
9.2.8.	3	Highway and railwood truss bridges, spans 250ft. to 550ft. (See figure title for effects of orientation.)	Total failure of lateral bracing, collapse of bridge.	Some failure of lateral bracing such that bridge capacity is reduced about 50%.	Capacity of bridge unchanged. Slight distortion of some bridge components. (Use q = 0.6 psi curve scaled to weapon yield.)
9.2.8.	4	Floating bridges, U.S. Army Standard M-2 and M-4, random orientation.	All anchorages torn loose, connections between treadways or balk and floats twisted and torn loose, many floats sunk.	Many bridle lines broken, bridge shifted on abutments, some connections between treadways or balk and floats torn loose.	Some bridle lines broken, bridge capacity unimpaired.
9.2.9.	1	Oil tanks, 30ft. in height, 50ft. in diameter. (Tanks considered full; more vulnerable if empty.	Large distortions of sides, seams split, so that most of contents are lost.	Roof collapsed, sides above liquid buckled, some distortion below liquid level.	Roof badly damaged.

9.2. Buildings and Surface Structures

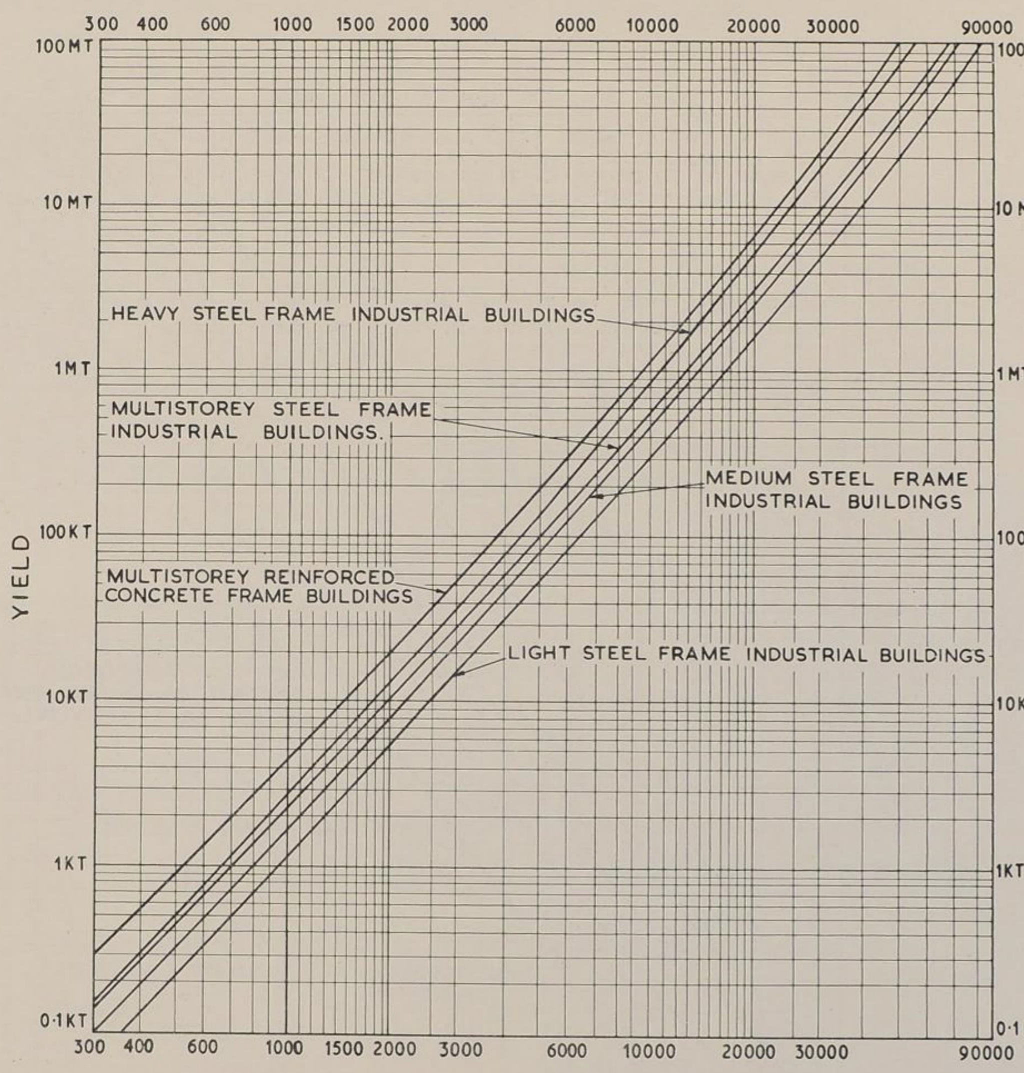
9.2.1. General Data For a given height of burst and yield, structural characteristics such as mass, strength, ductility, design detail and wall position including components, are the major influences on the structural response. Values of the vertical and horizontal loading components vary with the angle of elevation of the burst. Directly underneath the burst the roofs of structures may be dished in or destroyed and the walls collapsed, but there is no tendency to displace the structure laterally. Farther out, the horizontal component of the loading becomes more important, and damage under these circumstances may be greater because of the small lateral resistance of structures in comparison with their vertical resistance. Generally, damage at the same overpressure increases with yield because loading duration increases with increasing yield.

The importance of burst height varies with yield. For most structural types, variations in burst height up to 400 $W^{\frac{1}{3}}$ft. cause little change in the distance to which a given degree of damage extends. Figures 1 and 2 show the yield/distance relationships for various types of structures for a low air or surface burst (less than 400 $W^{\frac{1}{3}}$ft.). These curves are drawn for a 50% probability of attaining severe damage and may be used for other probabilities or damage levels as described in Section 9.1.5, or for underground bursts as described in Section 9.1.6. Typical examples of severe, moderate and light damage are given in Table I of Section 9.1.4.



DAMAGE TO TARGETS MAINLY SENSITIVE TO OVERPRESSURE

BURST HEIGHT BETWEEN ZERO AND 400 $W^{\frac{1}{3}}$ FEET
50% PROBABILITY OF SEVERE DAMAGE
TO CONVERT TO OTHER CRITERIA SEE SECTION 9.1.5.
FOR DAMAGE DESCRIPTIONS SEE SECTION 9.1. TABLE 1.



DAMAGE TO TARGETS MAINLY SENSITIVE
TO DRAG PRESSURE

9.2.2. Reinforced Concrete Buildings - Figure 1 shows the relationship between height of burst and ground range for different yields of weapon used against 3-storey reinforced concrete blast-resistant structures with reinforced concrete walls. The structures in question have no windows. The light damage category does not arise in the case of this type of structure. Figure 2 applies to 5-storey reinforced concrete buildings with un-reinforced concrete walls and a small window area.

Appropriate damage definitions in both cases are given in Section 9.1.4, Table I. These curves are for 50% probability of severe damage; adaptation to give other damage levels or probabilities of damage is described in Section 9.1.5. The allowances to be made in the case of airblast damage from underground bursts are given in Section 9.1.6.

9.2.3. Reinforced Concrete Frame Office Type Buildings - Figure 1 has been derived for 5-storey reinforced concrete frame office type buildings in which the lightweight low strength walls fail quickly. The structure is therefore regarded as primarily sensitive to drag forces for severe damage involving distortion of the frame. It is more nearly a pressure-sensitive target for lower damage levels. The curves relate to 50% probability of severe damage and may be adapted to other damage levels and for airburst damage for underground bursts as described in Sections 9.1.5. and 9.1.6. The damage levels are exemplified in Table I of Section 9.1.4.

9.2.4. Steel Frame Office Type Buildings - The curves of Figure 1 correspond to those given in Section 9.2.3, Figure 1 for similar buildings with reinforced concrete frame, and the remarks of that section apply equally to steel frame buildings.

9.2.5. Steel Frame Industrial Buildings with Light Walls - Figures 1, 2 and 3 apply respectively to heavy, medium and light industrial steel frame structures, the distinctions between the three being in terms of the crane capacity within. Heavy buildings are assumed to contain a crane of 50 tons capacity, medium 20 tons, and light, 5 tons. In each case it is assumed that the walls are of light weight and low strength, and that these therefore fail at an early stage of damage. Typical examples of severe, moderate and light damage are given in Table 1 of Section 9.1.4. The adaptation of these curves to give other damage levels or probabilities of damage is described in Section 9.1.5. The allowances to be made in the case of airblast damage from underground bursts are given in Section 9.1.6.

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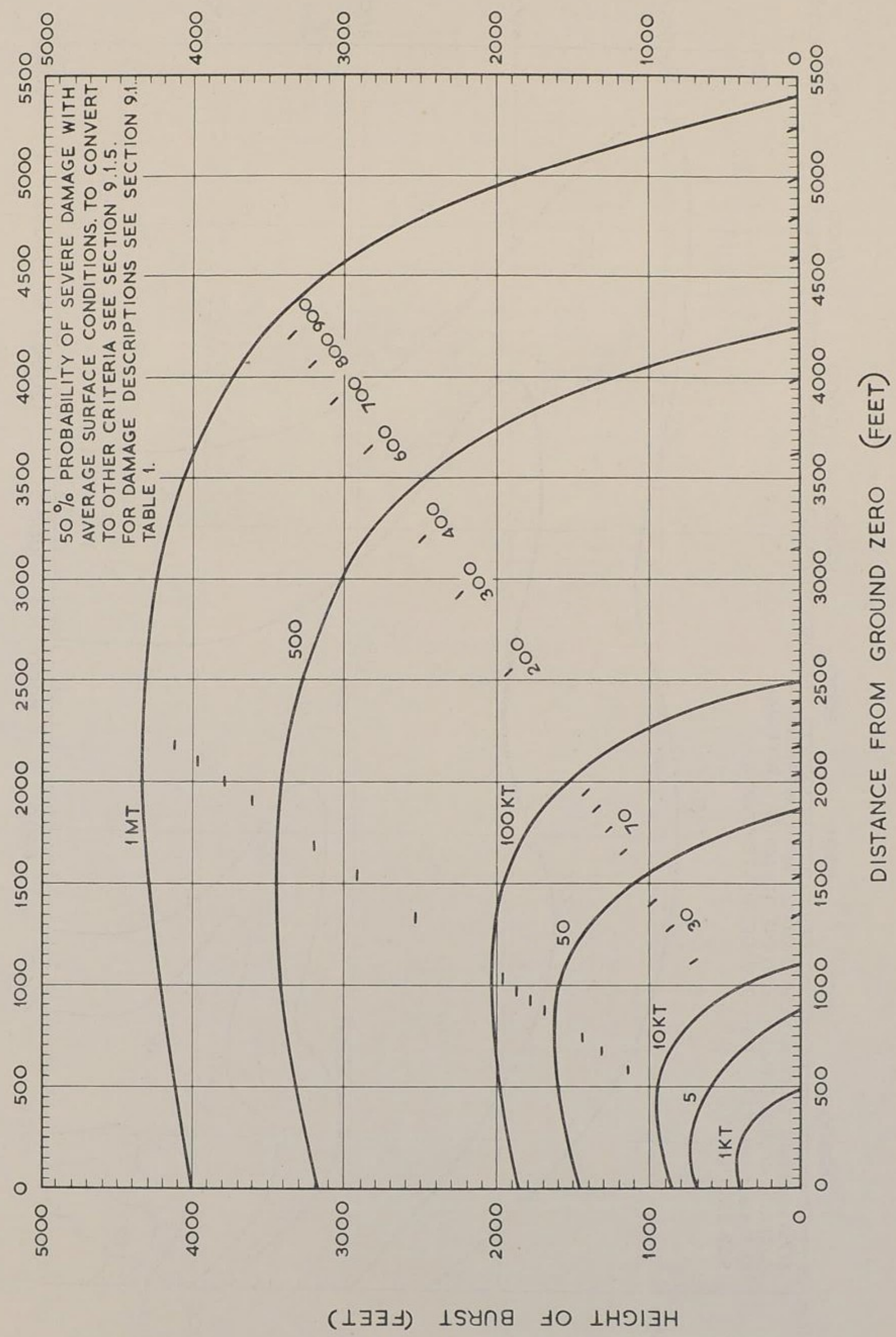
SEPT. 1957

PART III
CHAPTER 9.
SECTION 9.2.2.
FIGURE 1.



DAMAGE TO REINFORCED CONCRETE 3-STOREY CITADELS WITH REINFORCED CONCRETE WALLS.

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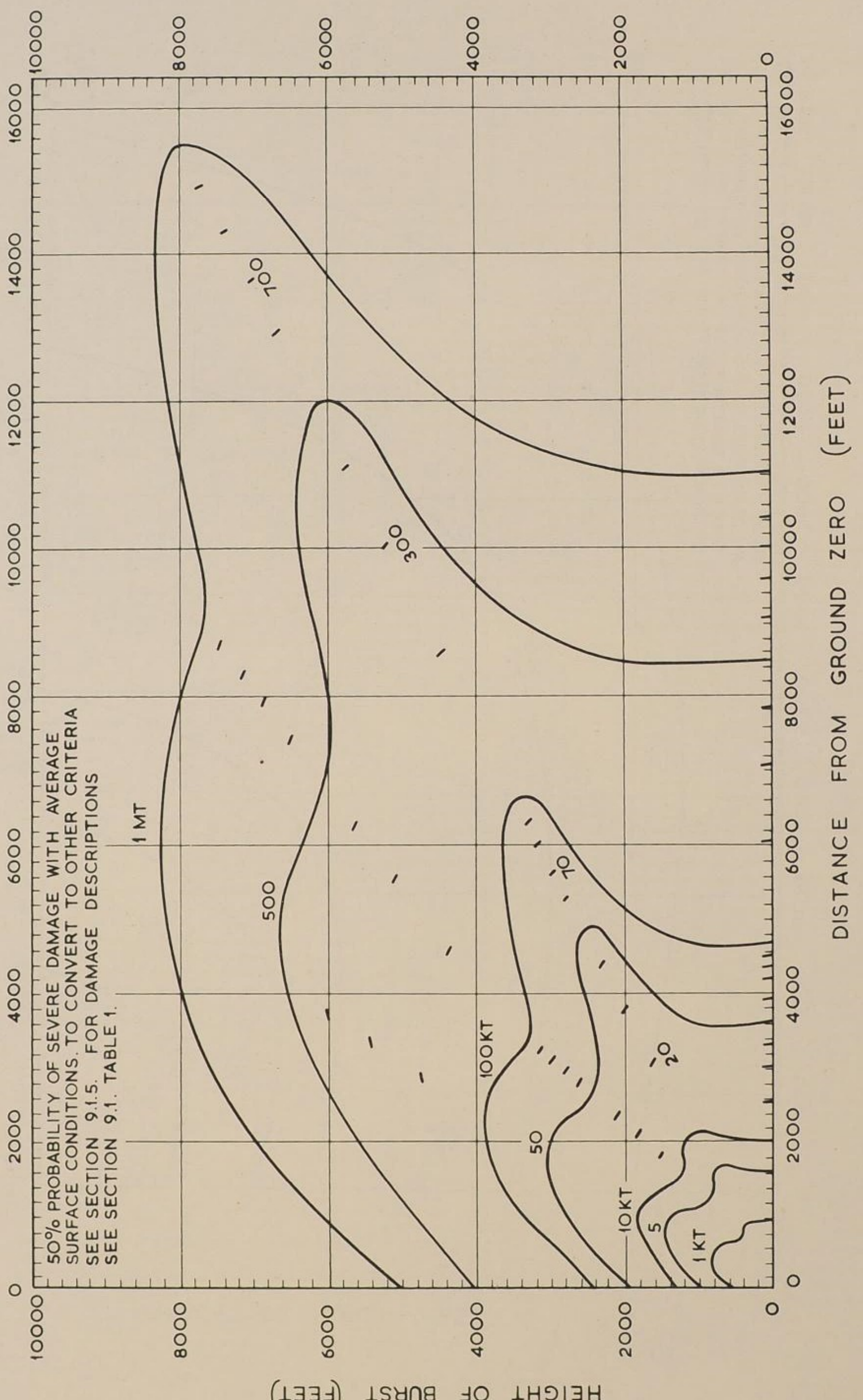
PART III
CHAPTER 9
SECTION 9.2.2.
FIGURE 2



DAMAGE TO REINFORCED CONCRETE 5-STOREY BUILDINGS WITH UNREINFORCED CONCRETE WALLS.

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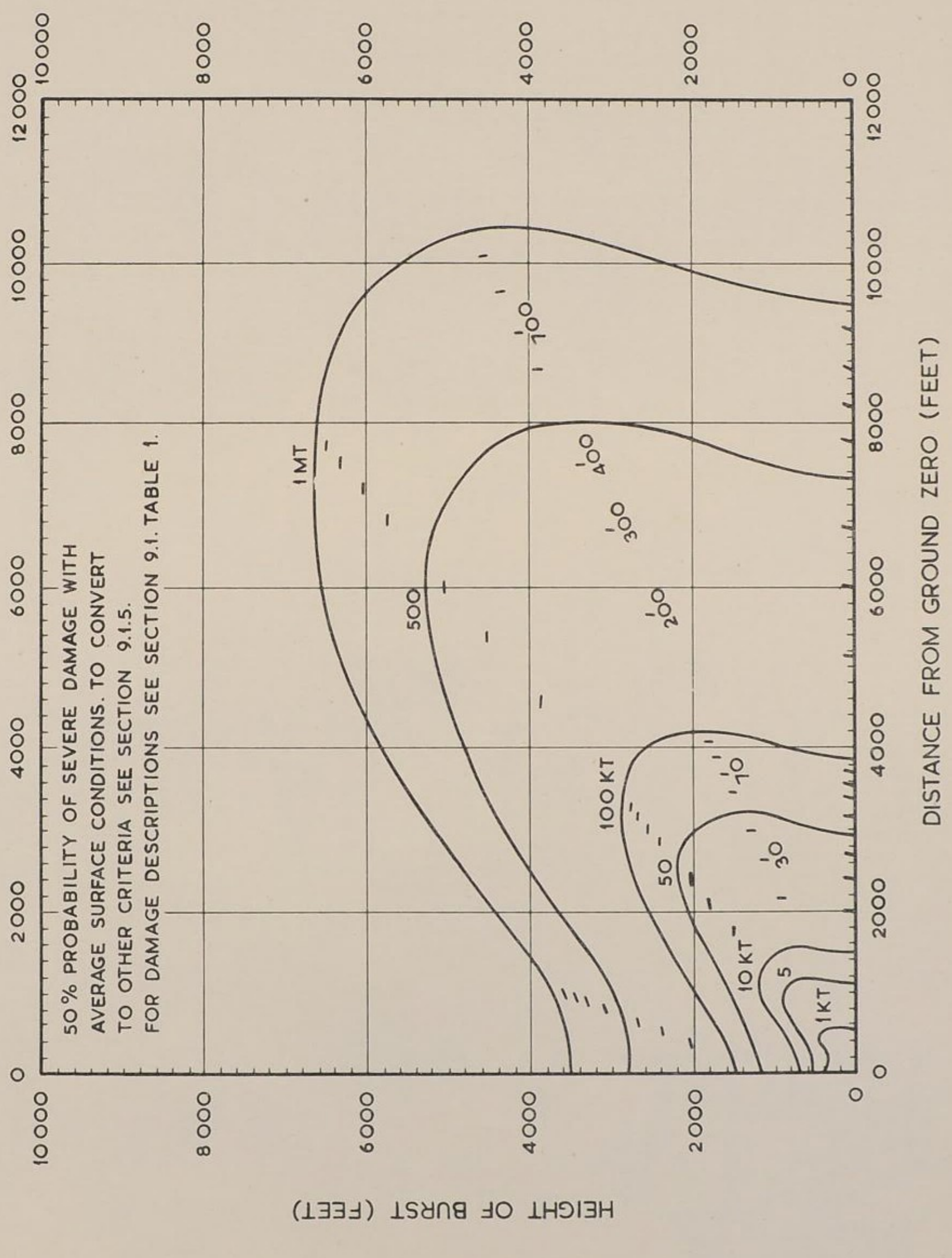
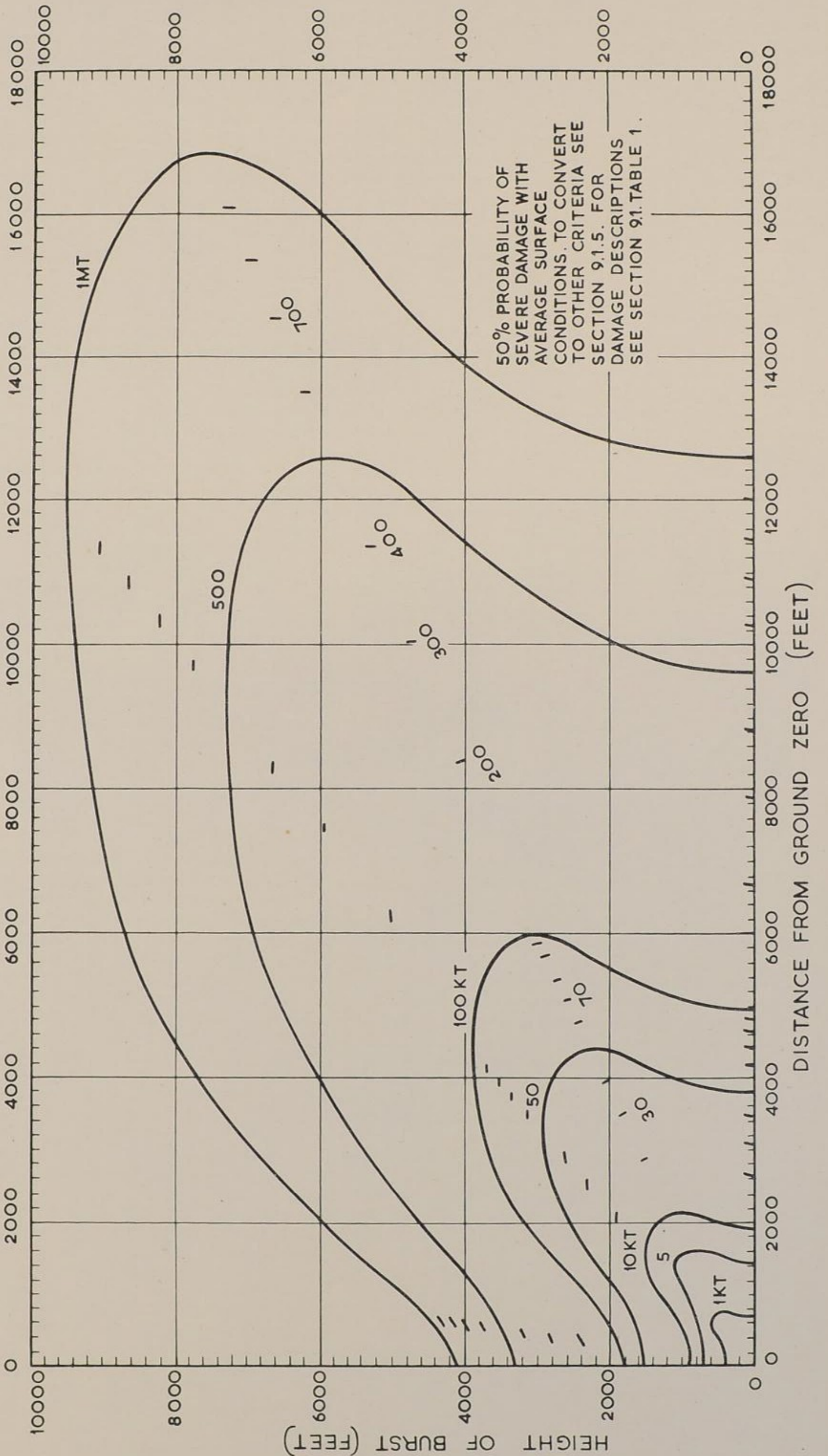
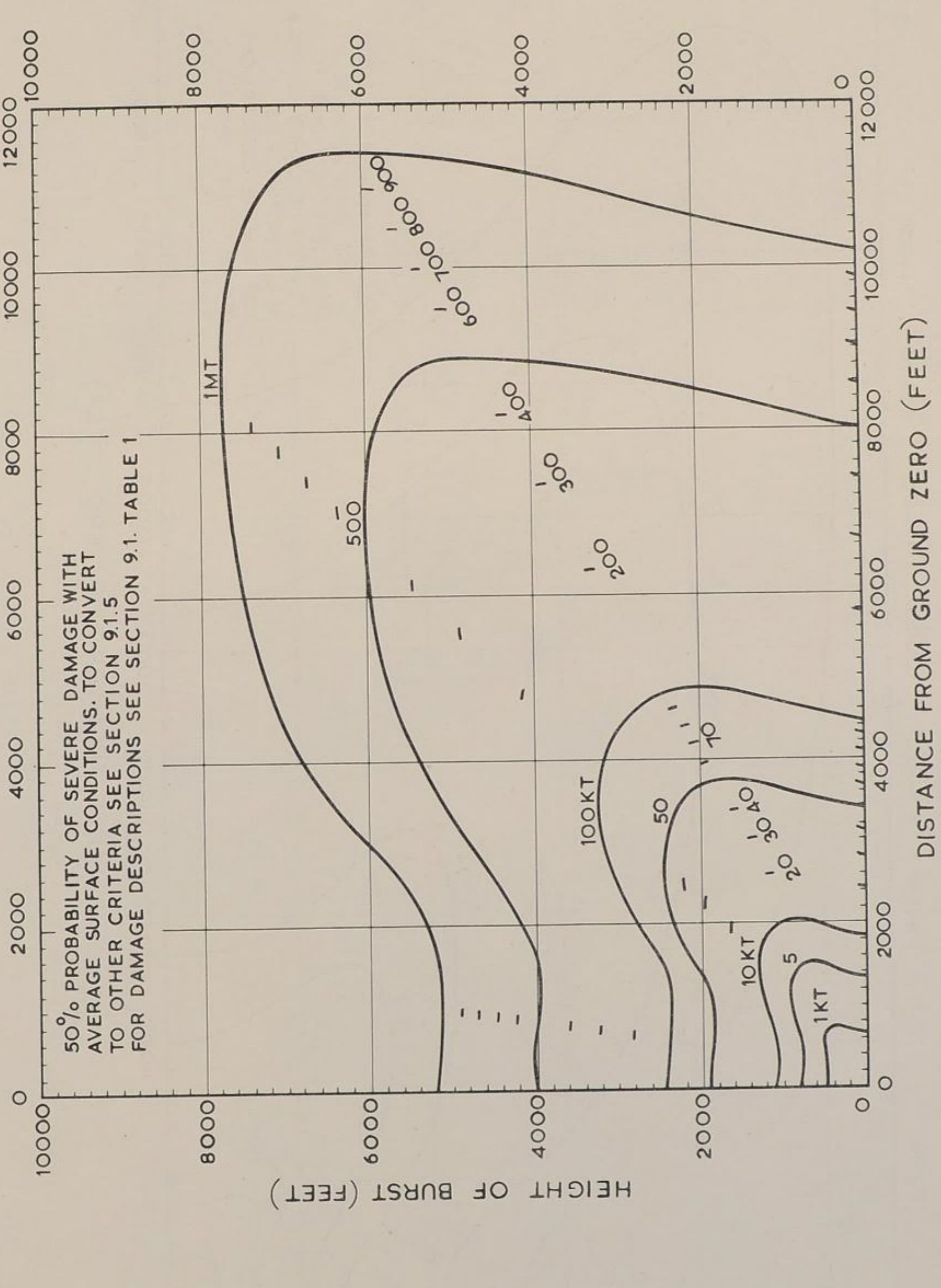


DAMAGE TO 5-STOREY REINFORCED CONCRETE FRAME OFFICE-TYPE BUILDINGS WITH LIGHT WALLS.



DAMAGE TO 5-STOREY STEEL FRAME OFFICE-TYPE BUILDINGS WITH LIGHT WALLS



DAMAGE TO HEAVY STEEL FRAME INDUSTRIAL BUILDINGS WITH LIGHT WALLS

SECRET ATOMIC

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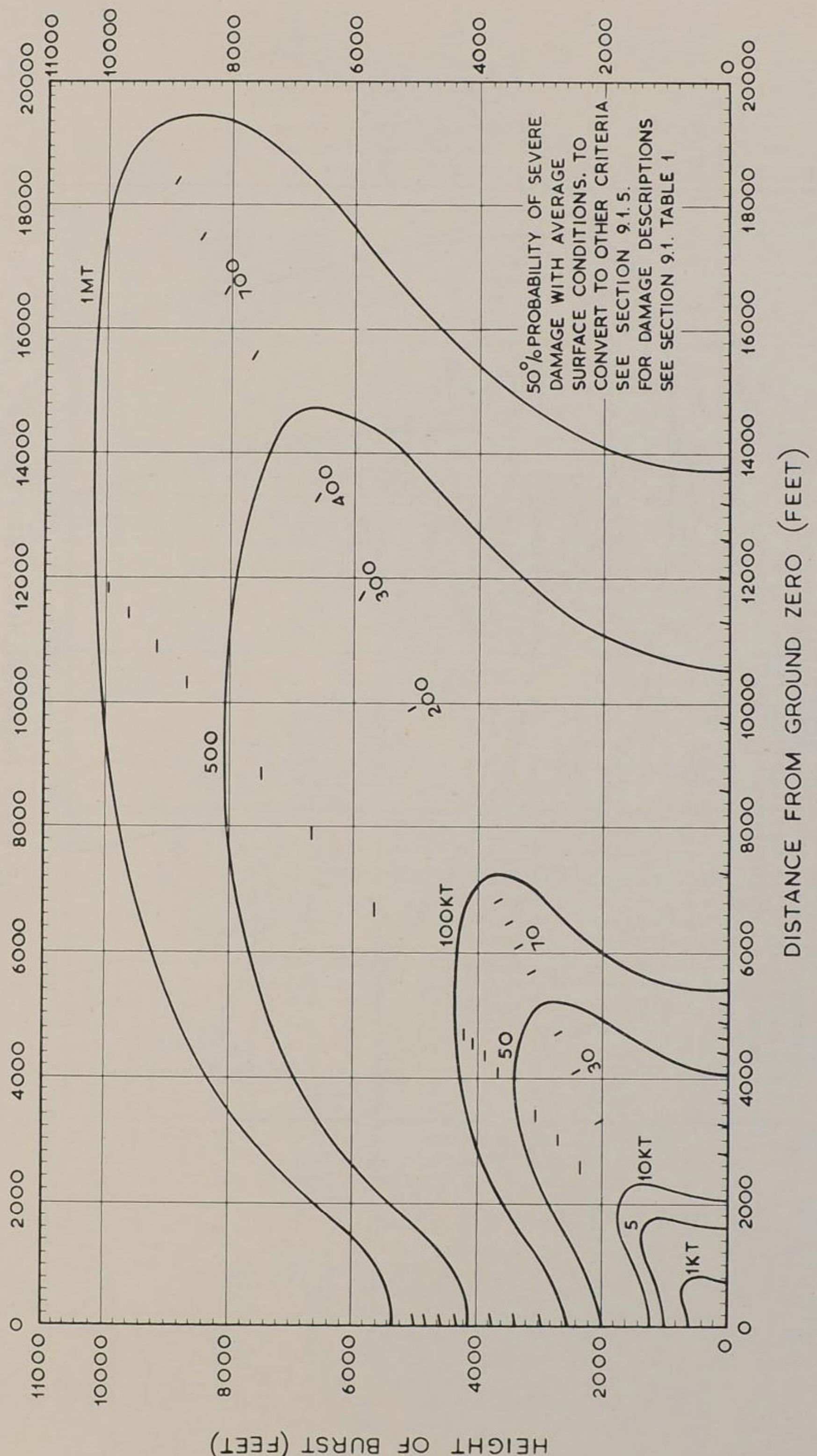

DAMAGE TO MEDIUM STEEL FRAME INDUSTRIAL BUILDINGS WITH LIGHT WALLS

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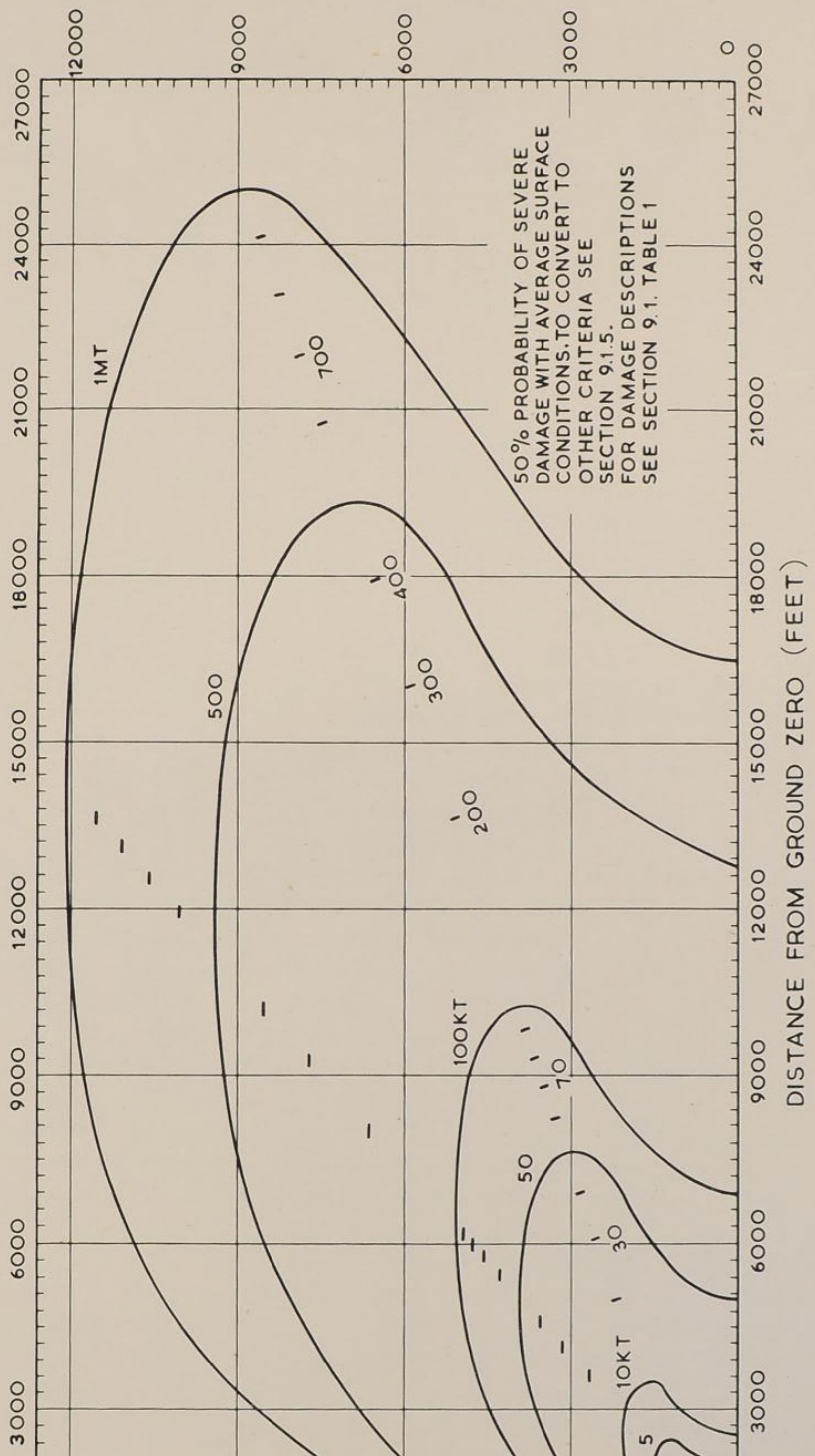
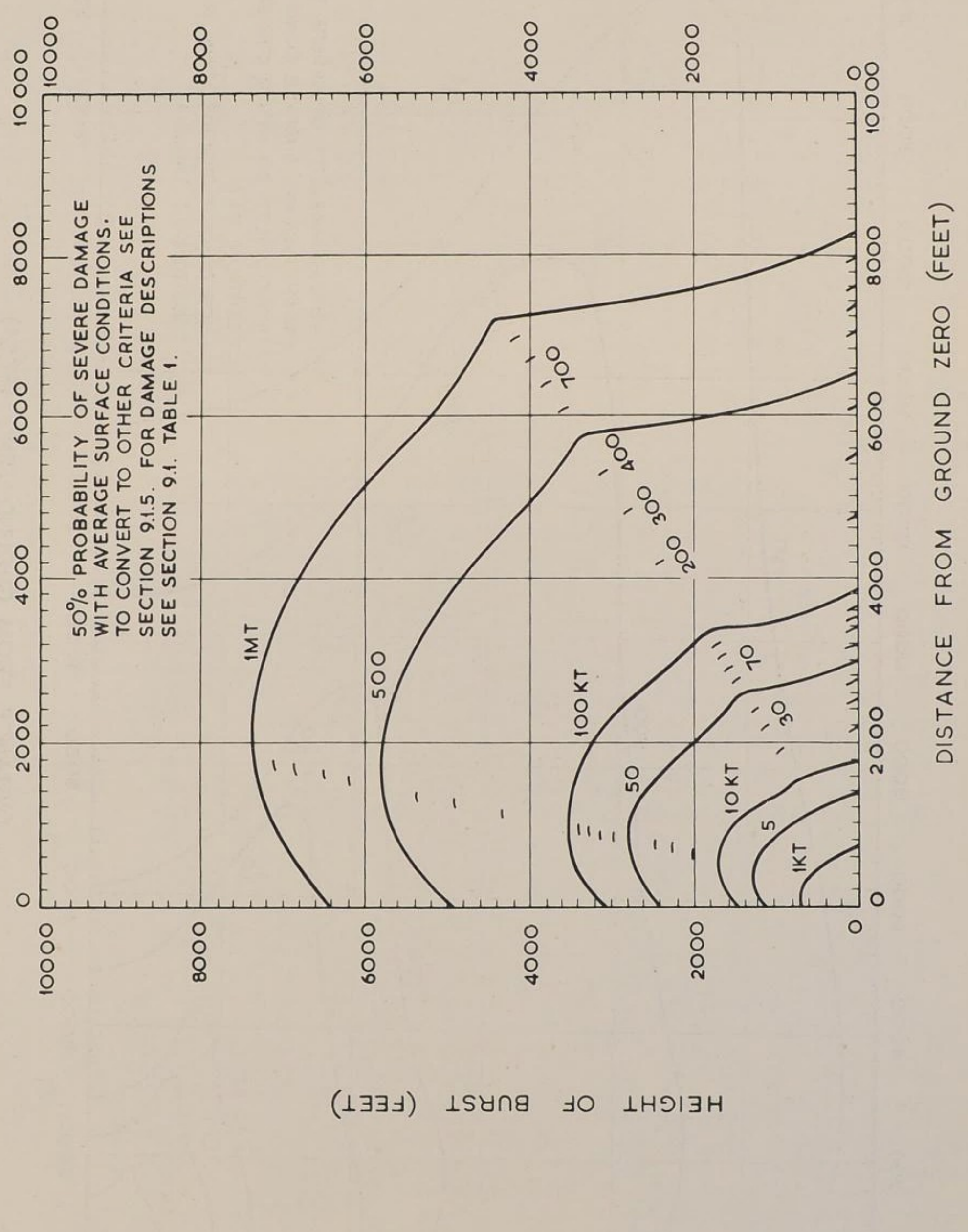
SECRET ATOMIC



DAMAGE TO LIGHT STEEL FRAME INDUSTRIAL BUILDINGS WITH LIGHT WALLS

9.2.6. Buildings with Load-Bearing Walls - Figures 1 and 2 apply respectively to heavy and light types of structure in which the main structural loads are carried directly by the walls. Ordinary brick-built houses are normally built in this way. For such structures, severe damage to the walls will result in total collapse of the building. As brickwork has relatively little strength in tension, structures which survive the initial loading may fall apart during the later parts of the blast, if appreciable blast has entered the building and cannot escape as fast as the external pressure is falling. Typical examples of severe, moderate and light damage are given in Table I of Section 9.1.4. The adaptation of these curves to give other damage levels or probabilities of damage is described in Section 9.1.5. The allowances to be made in the case of airblast damage from underground bursts are given in Section 9.1.6.

9.2.7. Wooden Frame Buildings - The curves of Figure 1 apply to single and 2-storey wooden frame houses. As woodwork has relatively little strength when cracked, structures which survive the initial loading may fall apart during the later parts of the blast, if appreciable blast has entered the building and cannot escape as fast as the external pressure is falling. Typical examples of severe, moderate and light damage are given in Table I of Section 9.1.4. The adaptation of these curves to give other damage levels or probabilities of damage is described in Section 9.1.5. The allowances to be made in the case of airblast damage from underground bursts are given in Section 9.1.6.



DAMAGE TO MONUMENTAL TYPE 4-STOREY
BUILDINGS WITH LOAD-BEARING WALLS

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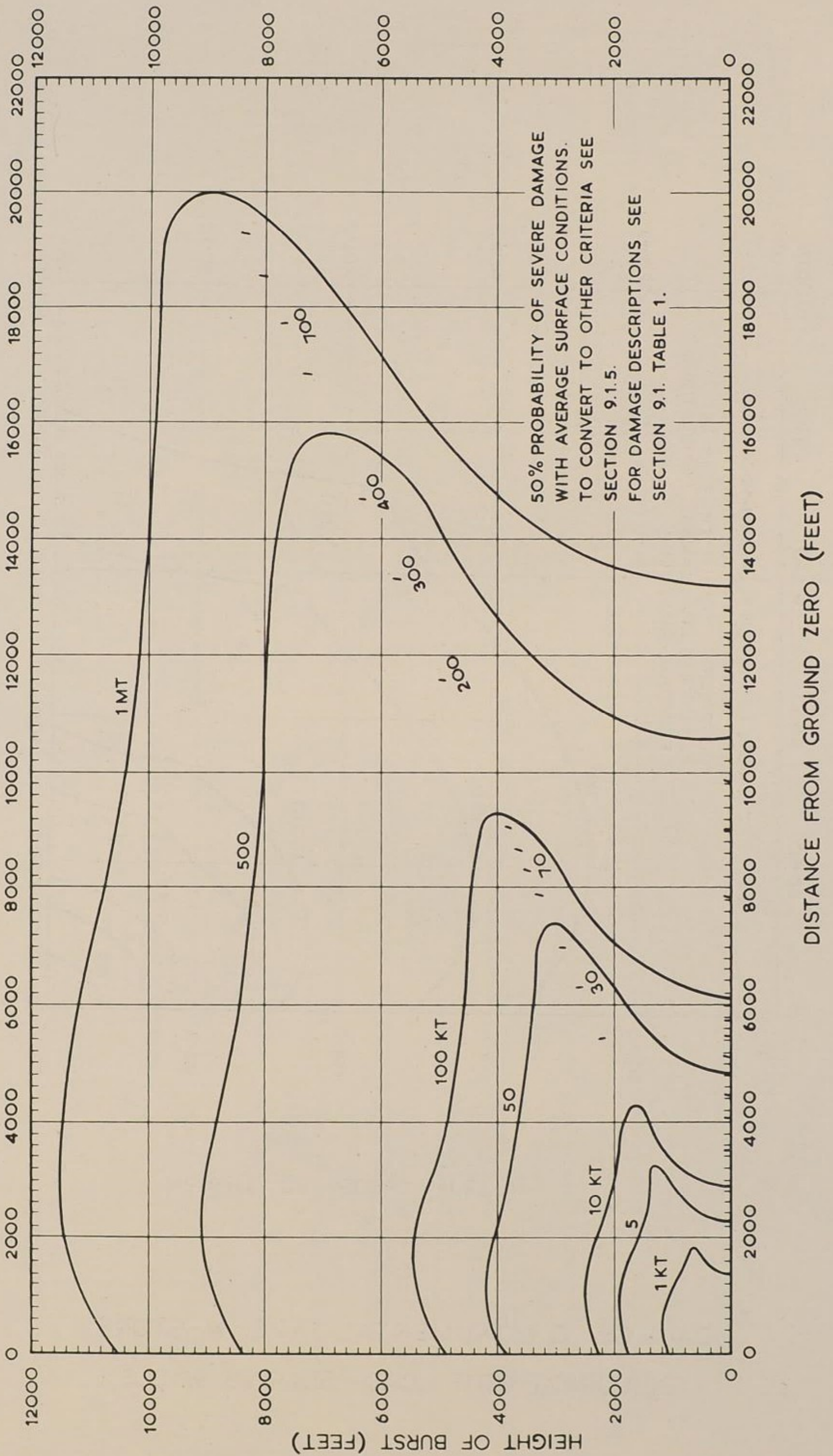

DAMAGE TO U.S. APARTMENT-HOUSE TYPE
BUILDINGS UP TO 3 STOREYS

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SECRET ATOMIC

TABLE 6.2

Response of Reinforced Concrete Roof Slab to Air Blast

t m.sec.	Δt m.sec.	Δx assumed ins.	$\overline{P(t)}$ p.s.i.	$\overline{F(x)}$ p.s.i.	$\frac{\Delta x}{\Delta t}$ ins/sec.	$\overline{\ddot{x}}$ in/sec^2	$\Delta \dot{x}$ in/sec.	$\dot{x}$ in/sec.	$\bar{\dot{x}}$ in/sec.	Δx ins.	x ins.
0								0			0
	5	.037	4.9	0.56	7.4	2927	14.64		7.32	.037	
5								14.64			.037
	5	.145	12.05	2.82	29.0	5729	28.64		28.92	.145	
10								43.28			.182
	10	.475	11.14	7.40	47.5	981	9.81		48.18	.482	
20								53.09			
	10	.480	11.14	7.42	48.0	947	9.47		48.01	.480	
20								52.75			.662
	10	.473	10.38	9.20	47.3	-902	-9.02		48.24	.482	
30								43.73			
	10	.480	10.38	9.21	48.0	-936	-9.36		48.07	.481	
30								43.39			1.143
	10	.373	10.67	10.24	37.3	-1081	-10.81		37.98	.380	
40								32.57			
	10	.378	10.67	10.25	37.8	-1107	-11.07		37.85	.378	
40								32.32			1.521
	10	.206	9.25	10.92	20.6	-2006	-20.06		22.27	.223	
50								12.26			
	10	.217	9.25	10.95	21.7	-2069	-20.69		21.97	.220	
50								11.63			
	10	.219	9.25	10.95	21.9	-2077	-20.77		21.93	.219	
50								11.55			1.740
	10	.031	9.07	11.21	3.1	-1697	-16.97		3.06	.031	
60								-5.42			1.771

Maximum central deflection $= \frac{1.77}{0.38} = 4.65$ inches

References

(1) Johnston, B.G. "Structural Steel Members and Frames"
Paper in Proceedings of Symposium on Earthquake and Blast Effects on Structures
University of California (June, 1952) ~~(Confidential)~~

6.2.2. Semigraphical Method.

This method, also known as the phase-plane method, was first proposed by Lamoen, Reference (1). The application of this to a wide range of problems is described by Jacobsen, Reference (2).

In the basic equation of motion (6.3) the resistance function F(x) is generally linear for small displacements, the slope of this linear portion being the "spring constant" k. Write

$$\omega^2 = k/M, \text{ and } \delta = \frac{1}{k}\left[b\dot{x} + F(x) - kx - P(t) \right]$$

If F(x) is not linear for small displacements, an arbitary convenient value for k may be chosen. Then the basic equation of motion takes the form

$$\ddot{x} + \omega^2 (x + \delta) = 0 \qquad (6.9)$$

Over a short enough interval of time during which δ may be taken as constant, this equation is of the simple harmonic type, e.g. that for the displacement of a spring of frequency $\frac{\omega}{2\pi}$, from a rest position at $\alpha = -\delta$. At a subsequent instant, when the value of has changed, the motion is part of another Simple Harmonic Motion, and the principle of the present method is to build up the whole motion approximately from a succession of small arcs of S.H.M.

It may be recalled that S.H.M. is susceptible of a graphical representation (see Fig.1) in which the point C rotates with anti-clockwise angular velocity ω around a centre at $(o, -\delta)$. In this case the ordinate ON represents the displacement x and the abscissa NC represents $\dot{x}/\omega$, i.e. is proportional to the velocity. The radius r is the amplitude of the motion, and in time Δt the angular change is $\Delta\theta$, where

$$\Delta t = \frac{1}{\omega}\Delta\theta \qquad (6.10)$$

Thus positive time is proportional to anti-clockwise rotation in this "phase-plane" diagram.

The whole phase - plane trajectory is composited of circular arcs, starting from the correct point corresponding to the initial conditions, and allowing for the continuous change in δ and r from instant to instant. The major difficulty in applying this method lies in calculating the value of δ to be used in each time interval. This may be done most easily with the aid of subsidiary graphs of the components of δ, i.e.

$$\frac{b}{k}\dot{x}, \ \frac{F(x)}{k}, \ \text{ and } \ \frac{P(t)}{k},$$

on the same scale as those of the main phase - plane diagram. It is a further help to draw out the graph of $\left[\frac{F(x)}{k} - x\right]$ as a function of x.

Figure 2 shews the phase - plane method applied to the example of Section 6.2.1. The phase - plane trajectory is drawn in graph (C), the the components of δ in graphs (A), (B), and (D).

Comparing equations (6.8) and (6.9) we find

$$\frac{\omega^2 b}{k} = 37.5\frac{\omega^2}{k} = 738.5$$

and also from the static load/deflection curve F(x) of Section 5.2.3 Figure 1, we find

$$\frac{1}{k} = 0.032 \text{ inch/p.s.i.}$$

so that

$$\omega = 152 \quad \sec^{-1}$$

From equation (6.10) the angle/time factor in the phase - plane is 57.3 X 152 degrees per second, or 8.22 degrees per millisecond. A constant time interval of 5 milliseconds hae been used in this example, so that the phase trajectory consists of a series of circular arcs, each subtending 41.1 degrees. It is important to note that the same scale is used in all axes, otherwise the arcs would not be circular.

In graph (A) the function $\left(\frac{F(x)}{k} - x\right)$ is plotted horizontally against a vertical scale of x. This function is obtained from the load/deflection curve of Section 5.2.3., Figure 1. In graph (B) the blast loading is plotted vertically as $\frac{P(t)}{k}$ against a horizontal time scale. In graph (D) the damping force $\frac{b\dot{x}}{k}$ is plotted vertically against $\frac{\dot{x}}{\omega}$. This is a straight line of slope $\frac{b\,\omega}{k} = \frac{37.5}{152} = 0.247$, that is, twice the critical damping ratio.

As the panel is initially at rest and undeflected, (ignoring the dead-weight loading), the trajectory starts at the origin of graph (C). The average value of $\frac{P(t)}{k}$ during the first time interval is found from graph (B) and set on compasses. The position of the first arc Oa is then estimated and the average values of $\left(\frac{F(x)}{k} - x\right)$ and $\frac{b\dot{x}}{k}$ for this arc are found from the appropriate graphs. These are subtracted from the setting of the compasses, giving the value of $-\delta$ for the first step. Note that $\left(\frac{F(x)}{k} - x\right)$ is always zero or negative in this example so that the length is actually added to the compass setting. This gives the position of the first centre A, and the arc Oa is drawn with the same radius, making the angle OAa 41.1 degrees. If this arc does not agree with the assumed arc, the position of A is adjusted until agreement is obtained. This adjustment can very easily be made by eye.

This procedure is repeated for the second time interval, the compass setting giving the length OB, and the second arc ab is drawn from centre B and radius Ba, to subtend an angle of 41.1 degrees at B. The rest of the trajectory is constructed in the same manner. The maximum deflection of the panel is given by the intersection of the trajectory with the X - axis. The trajectory can then be transposed to the time - scale of graph (B) to give the deflection/time curve for the panel.

The phase - plane graphical result is compared with the numerical integration in table 6.3. The two methods agree to within 5 per cent.

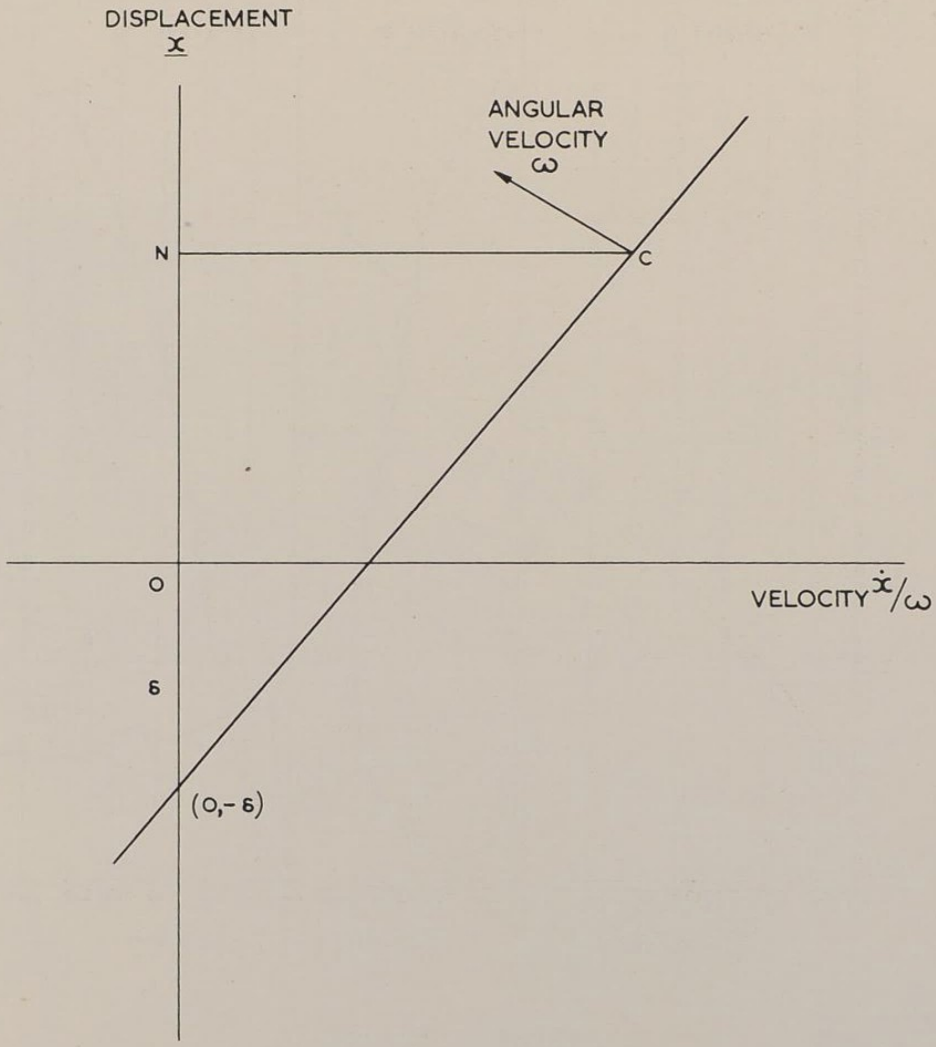
Table 6.3

Time (millisecs)	Average Deflection (inches) (a) Numerical Integration	(b) Phase-Plane
0	0	0
5	0.037	0.04
10	0.182	0.18
20	0.662	0.67
30	1.143	1.13
40	1.521	1.47
50	1.740	1.72
60	1.771	1.78

References.

(1) Lamoen, J. Revue Universelle des Mines, 8e Serie, Tome II, No.7 (1935).

(2) Jacobsen, L.S. J.Appl.Mech. 19, 543 (1952).



PRINCIPLE OF THE PHASE PLANE METHOD

UNCLASSIFIED

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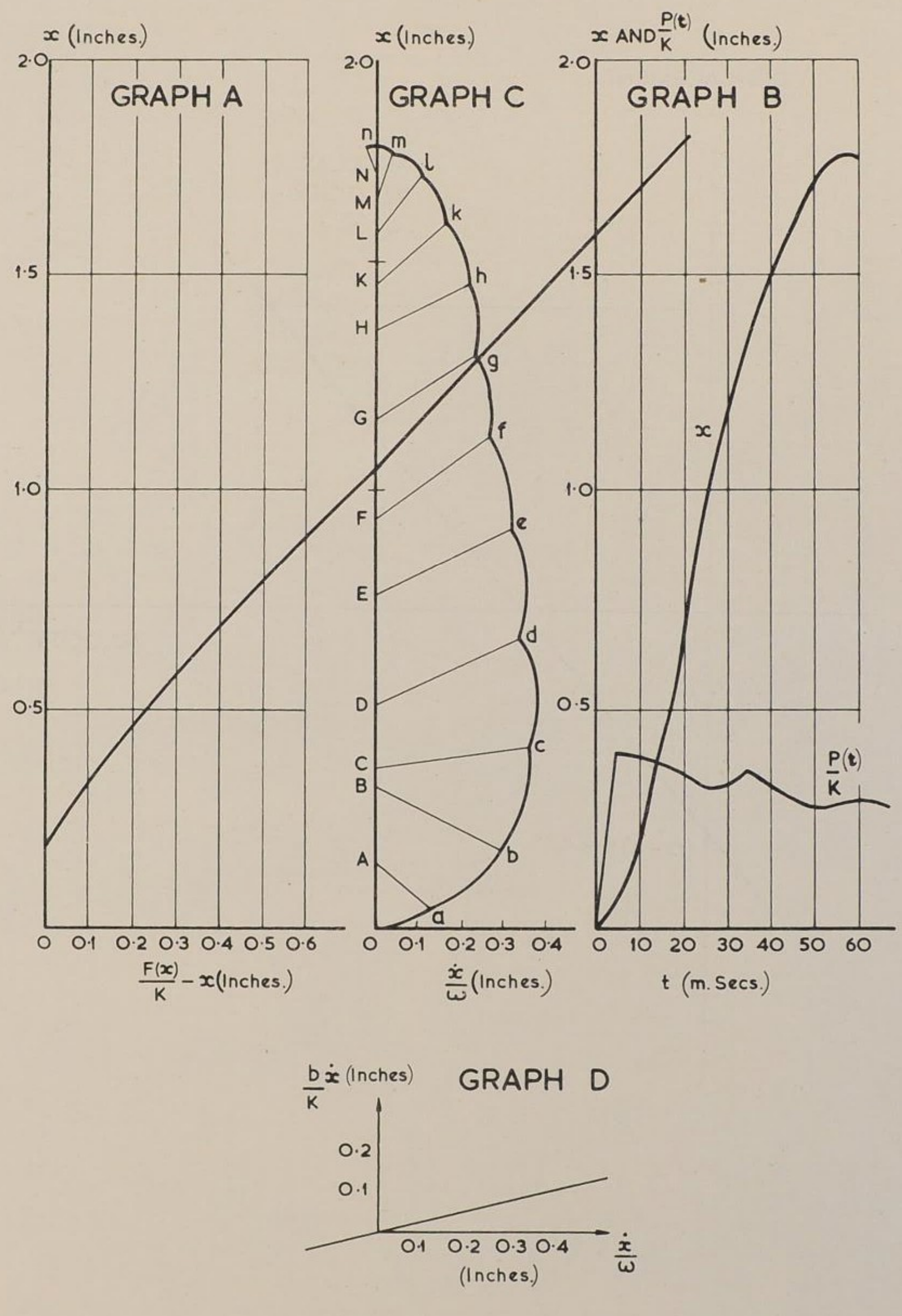


SEMI-GRAPHICAL SOLUTION OF RESPONSE OF R/C PANEL

UNCLASSIFIED

6.2.3. Analytical Method

If the graphs of blast pressure P(t) and static resistance F(x) have a reasonably smooth and simple shape, they may, without much error, be replaced by integrable analytic functions, and equation (6.3) can then be integrated directly. A series of linear segments is usually used to represent F(x), while P(t) is usually given an exponential form (see Section 2.2).

The chief advantage of an analytical solution is that it can be presented graphically as families of curves covering a wide range of blast and structural parameters, but before using such graphs one must be careful to check whether the assumed analytical functions for F(x) and P(t) reasonably represent the problem on hand.

Examples of the analytical method will be found in the references.

References

(1) Lehigh University. "Bomb Damage Analysis" Final Report Volume III (1949) (Confidential/Discreet)

(2) Armour Research Foundation. "A Simple Method for Evaluating Blast Effects on Buildings" (1952) (Unclassified)

(3) A.W.R.E. Report E2/53 (Confidential)

(4) Thornhill, C.K. A Unified Theory of Damage from Minor External Blast. A.R.D.E. Report. B 24/57 (Confidential)

6.3. Presentation of Results

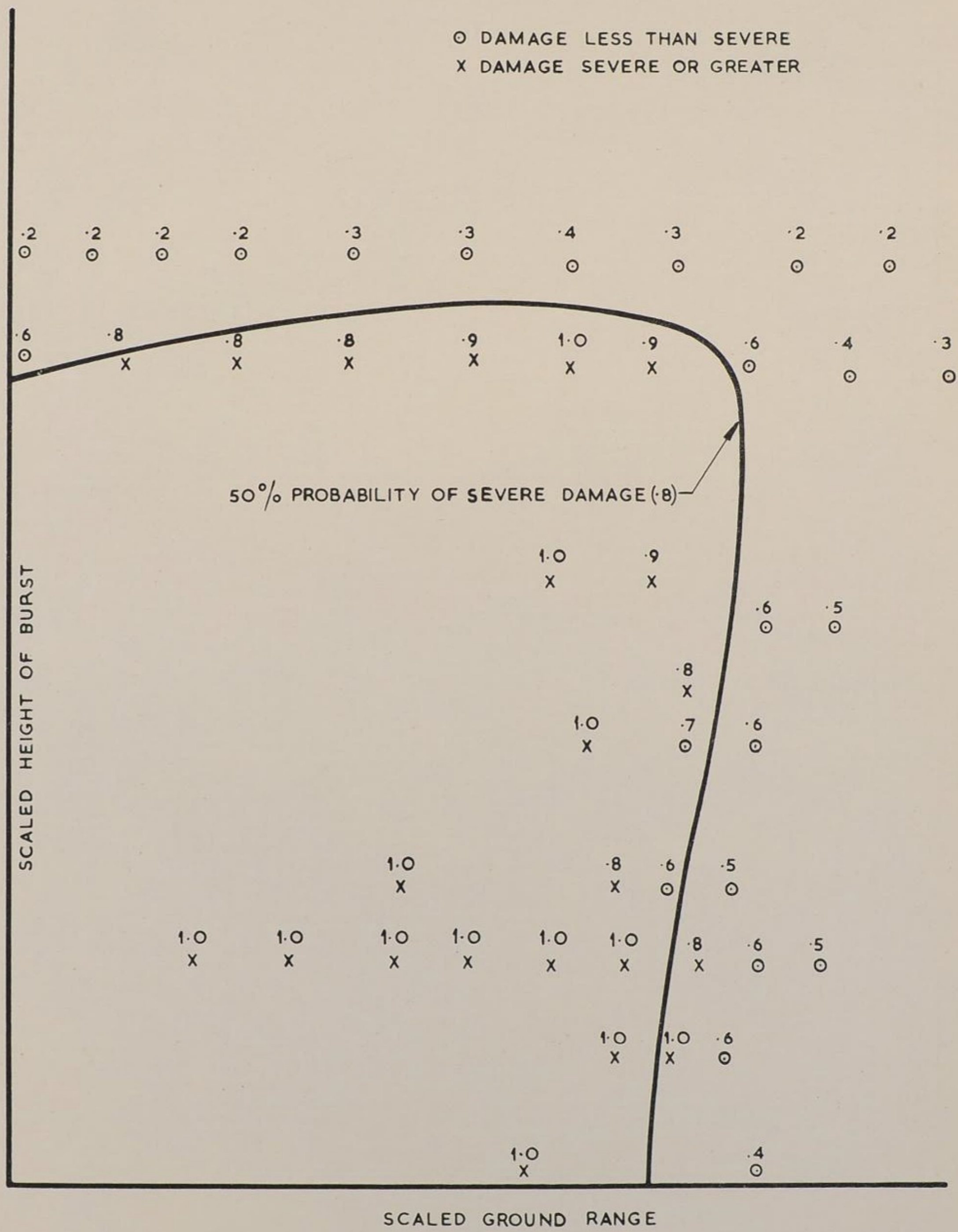
When response data have been obtained for a particular target, whether by calculation, model-scale experiments, full-scale weapons trials, or by a combination of these, the information has to be presented concisely so that it can be easily assimilated. A good method of doing this is to construct a set of isodamage curves as has been described by Hesse (1). The first step is to establish a numerical scale of damage. This could be based on the maximum deflection or permanent set of some part of the target, or on the amount of repair required to make the target fulfil its function again. The scale can conveniently range from 0 for no damage, to 1 for complete destruction. The next step is to establish the relationship between degree of damage and ground range for particular heights of burst and weapon yield. In general a given degree of damage will be produced by a lower incident overpressure from a large weapon than from a smaller one owing to the longer duration of the blast wave. For a given target therefore, the range for a given degree of damage will vary as some power higher than $\frac{1}{3}$ in the weapon yield. The Americans have found (1) that for military field equipment the ground range for a given degree of damage varies as $W^{0.4}$ if a constant scaled height of burst (scaled as $W^{\frac{1}{3}}$) is considered. The power 0.4 will probably be different for other types of target and may not apply to very large yields.

Having established the scaling law for ground range, the isodamage curves can be constructed on axes of scaled height of burst ($W^{\frac{1}{3}}$) and scaled ground range (empirical scaling law). A schematic example is given in Figure 1. Similar curves can be constructed for other degrees of damage. Extensive use is made of this type of curve in chapter 9 for presenting the generalised empirical data from Reference (2).

References

(1) Hesse, Major R.J. AFSWP Conference on "Effects of Blast on Military Field Equipment", Washington (February, 1956) (Secret/Discreet)

(2) Capabilities of Atomic Weapons AFSWP 1st June, 1955. Part II Damage Criteria (Secret/Atomic)



SCHEMATIC INDICATION OF CONSTRUCTION OF ISODAMAGE CURVE

CHAPTER 7 - DEBRIS

7.1 Damage by Flying Fragments

Glass

In regions of light structural damage (about 2 to 4 miles from a nominal bomb) fragments will consist mainly of window glass and roofing tiles and slates. The main hazard to life in these areas will be from flying glass. The size of the fragments will depend largely on the type of glass and on its quality and age; the condition of the putty or other edge support is also important. Ordinary sheet window glass usually breaks into long, thin fragments. Some information on the strength of different types of glass is given in Section 5.2.4.

The fragments will be quickly engulfed in the air stream flowing in through the window, and they will be accelerated by the 'drag' force acting on them. The velocity of the fragments at a distance of 10 feet from the window has been calculated approximately, and is shown by the curves of Figure 1 for 24 and 32 oz/sq.ft. glass and for 20 KT and 10 MT weapon yields. A scale of incident peak overpressure is also shown. Heights of burst of 2,500 ft. and 20,000 ft. respectively were assumed to give the maximum blast effect at this range. The velocities shown for a 20 KT weapon are practically the maximum velocities which would be obtained in free flight, but for a 10 MT weapon, owing to the longer duration of the blast, the maximum velocity would be about five times that attained at 10 feet.

A test with a 35 KT Tower burst gave the following results, for which the grade of window glass was not specified (Reference (1)):-

Range from burst .	4,700 ft.	10,500 ft. (1.7 p.s.i.approx)
Nature of Missile	Mostly glass, some rocks and sticks	Mostly glass
Glass velocities Minimum	52 ft./sec.	34 ft./sec.
Maximum	157 ft./sec.	145 ft./sec.
Maximum missile density	480/sq.ft.	3.7/sq.ft.

Masonry

At closer range (about $\frac{3}{4}$ to 2 miles from a nominal bomb) moderate structural damage will occur. Projections such as chimneys, and unanchored objects such as vehicles, will be caught and thrown by the blast wind. Much brickwork will be demolished, and it has been observed that side walls of buildings sometimes collapse outwards due to the blast pressure building up internally through openings in the wall facing the blast wave (see Section 4.1). The fragments of brickwork will again be caught by the blast wind and form dangerous projectiles. The size of the fragments will vary from dust to whole wall panels (if there is little edge fixation) weighing perhaps 10 tons. It is impossible to calculate the exact velocity distribution, but upper and lower limits could be estimated by using equations (1.1) and (1.4) for the drag force with a drag coefficient between 1 and 2, and by considering the maximum and minimum areas of presentation of a fragment to the blast wind. The effect of a precursor may considerably modify the debris distribution.

In areas of severe structural damage, additional damage by fragments is not likely to be important; the question of obstruction by debris is considered in the next section (7.2).

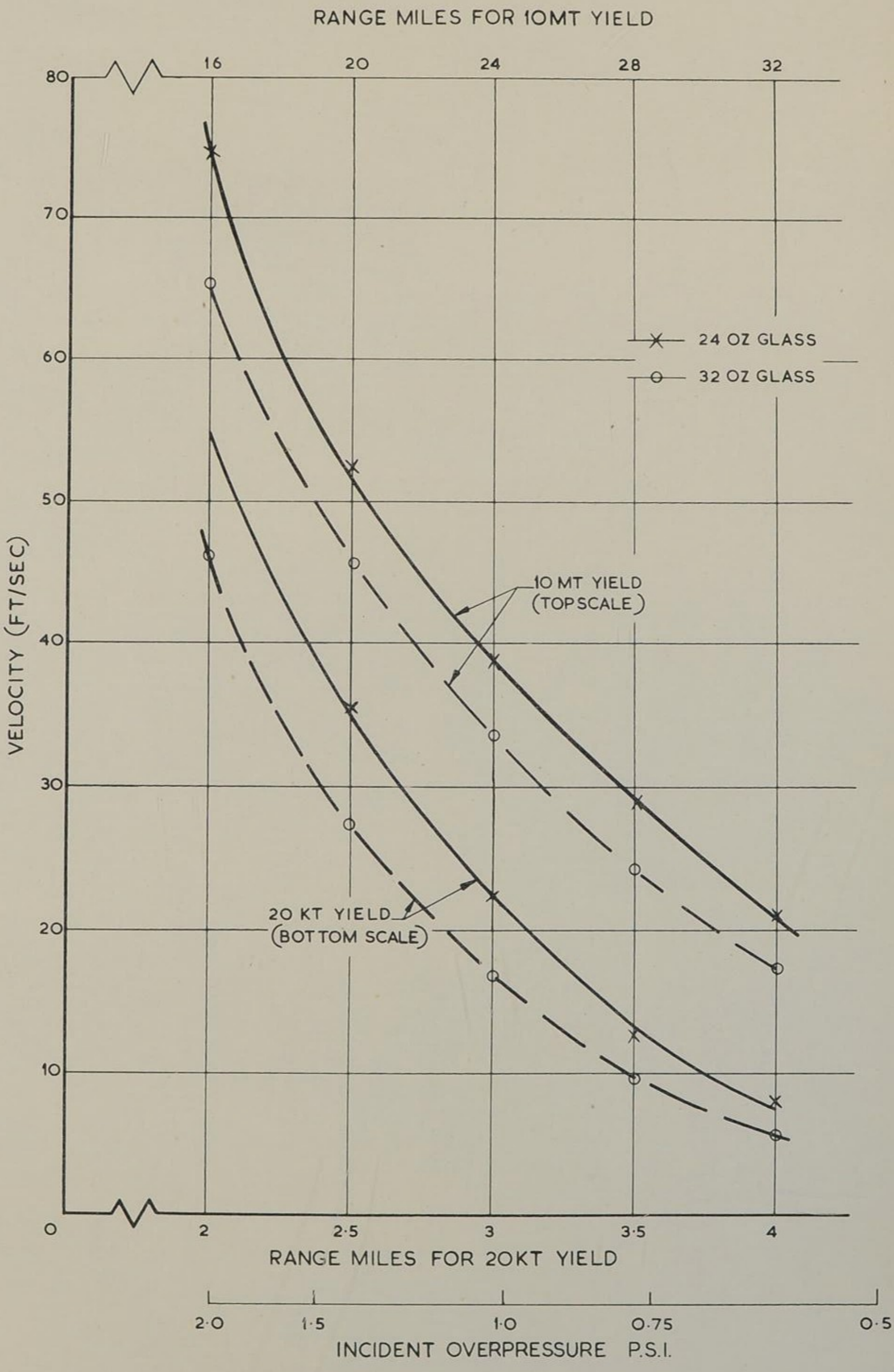
References

(1) Distribution and Density of Missiles from Nuclear Explosions.

Operation Teapot, 1955. Project 33.4. C.E.T.G. ITR-1168

(Confidential/Restricted Data)

(2) The effects of a Nuclear Explosion on Records and Records Storage Equipment Operation Teapot 1955.
Project 35.5. C.E.T.G. I.T.R.-1191 (Unclassified)



VELOCITY OF GLASS FRAGMENTS 10 FEET FROM WINDOW

7.2 Debris Distribution

The extent to which roads and open spaces are likely to be blocked by falling debris is of importance in both civil and military planning. An assessment of these effects for a 20 KT bomb has been made by the Ministry of Works (1). Five types of domestic and industrial buildings with load-bearing walls were considered. It was found, in general, that at a range of 2,000 ft. the debris would be spread in a fairly even layer over a distance of 1 to 2 times the height of the buildings. At a range of 5,000 ft. there would be very little scatter of debris.

At corresponding scaled distances from a megaton weapon the debris would be thrown very much further because of the longer duration of the blast wind, thus producing a still more uniform distribution of debris in directions radial to the blast.

Some Nevada trials results for heavy objects such as safes are given in Reference (2)

References

(1) Civil Defence (Inter-Departmental) Structural Precautions Research Committee. CD/SPR/137 (1954) (Secret)

(2) Operation Teapot. Project 35.5. The effects of a Nuclear Explosion on Records and Record Storage Equipment. Civil Effects Test Group: Preliminary Report ITR - 1191.

CHAPTER 8 - BIOLOGICAL EFFECTS OF BLAST

This Chapter is to be issued later.

The reader is meanwhile referred to Chapter 9, Sections 9.8. and 9.9. for general data, and to references (1) and (2) for summaries of British and American work.

References.

(1) Recent observations on the effects of blast on animals. August 1957. Professor Sir Solly Zuckerman. Ministry of Defence AWEC/P(57)38.(Confidential)

(2) The biological effects of blast.. A critical review. September 1954. Clayton S White. M.D. Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico. Report T.I.D.5251. (Confidential.Restricted Data.)

Chapter 8 - Blast Biology

8.1 Introduction

For the purpose of studying the injury caused to man the blast from nuclear weapons may be regarded as producing two effects: the static overpressure and the dynamic or wind pressure.

The first effect may cause injury by compression or rupture of air - containing viscera - bowels, lungs, etc. Studies of this direct effect of blast on animals were made at a British Trial and are summarised in Section 8.2 below. Estimates of the direct blast casualties to personnel in the open are given in Section 9.8.1 of Chapter 9.*

The second effect (dynamic pressure) will produce displacement of personnel with subsequent injury on striking fixed objects or the ground. This is dealt with in Section 8.3 below, which summarises some recent British work. Additional data are given in Section 9.8.2 of Chapter 9.

Injury to man may also be caused by missiles carried by the blast wind, or by the collapse of structures under blast loading. These aspects are discussed in Section 9.8.3 of Chapter 9.

8.2 Injury by Blast Overpressure

It is noted in Reference (1) that experiments were carried out during World War 2 to determine the relationship between the peak static overpressure of a blast wave and the proportion of exposed animals which received (a) fatal injuries (b) minimal damage to the lungs, and (c) ruptured ear drums.

The blast pressures required to produce similar injuries in man were obtained by extrapolation. The general conclusion was that the primary effect of blast represented an insignificant hazard to civilian or military personnel when compared to the other ways in which injury might be caused by high explosive weapons.

The development of nuclear weapons raised the possibility that the blast waves from nuclear explosions (whose duration was likely to be measured in seconds, and therefore outside the range already studied) might prove exceptionally damaging.

Trials with animals (goats, rabbits and mice) were therefore carried out at Operation Buffalo, to investigate the possibility that blast waves lasting for several hundred milliseconds would be more lethal for a given peak overpressure than the short-lived wave from a charge of ordinary high explosive. The results, which are reported in Reference (1), provide no reason for believing that the blast wave in this particular trial had any significant added lethality conferred on it by virtue of its long duration. Two reservations are set against this conclusion.

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*It should be noted that the material presented in Chapter 9 was obtained largely from the 1955 edition of the U.S. Publication "Capabilities of Atomic Weapons" (Secret Atomic), now superseded by an issue of November, 1957 (Confidential Discreet). The information on blast biology does not appear to differ greatly between the two editions, but where the reader has access to the 1957 "Capabilities" this should be used in preference to Chapter 9.

(1) The general character of the blast wave which struck the sites close in to Ground Zero was unlike the wave from conventional charges, and was influenced to an unknown extent by the earth walls which formed an indispensable part of the experimental layout.

(2) Even when the shape of the wave became more "normal" it still did not show the typical extremely rapid rise to peak pressure.

It must therefore be accepted that other types of weapons and other sites which might alter the shape of the incident wave might also influence the results obtained. Nevertheless, taking into account how much the effects of radiation and displacement contribute to the total lethality of the weapons, it is clear that the direct impact of the blast wave on human beings is not an important hazard.

8.3 Injuries caused by translational motion

An investigation into the displacement of personnel by the free air blast wave from Round 1 of Operation Buffalo is reported in Reference (2). It is noted in this report that the only previous enquiry into the problem was a theoretical study by Liston (Reference (3)), who calculated that a man weighing 12 stone standing 1300 yards from a 20 KT weapon would be displaced 20 ft. and suffer severe injuries. A like person at 2000 yards would be displaced 4 ft. and uninjured. Liston also predicted that a man lying prone at 1300 yards would be quite safe since his displacement would be insignificant. These predictions were checked by the experiments performed at Operation Buffalo.

Two modes of injury by the blast wind were envisaged for investigation:-

(1) If exposed to a sufficiently strong wind men would move bodily and receive injuries on striking fixed objects or the ground.

(2) The wind may cause sudden jerking movements of the limbs relative to the trunk. If sufficiently violent, these movements would cause dislocation of the joints or break bones.

The method of investigation was to use 30 articulated dummy men clad in battle dress and set out before the explosion of a weapon of approximately 15 KT, detonated on a tower. The dummies were set out in six orientations to the explosion, and each orientation was displayed at five ranges.

Description of Dummy Men

The dummies were designed to resemble men ballistically, to simulate as far as possible with inanimate objects the interaction between man and the blast wave. The model chosen for the experiments had been designed and developed by R.A.E., Farnborough (Reference (4)) for studies of seat ejection and restraint harnesses (Reference (5)). Consisting basically of mild steel, with cannisters for limb segments, the dummies were manufactured so that the total weight and segment weights and the centres of gravity of the various limbs, trunk and head were all appropriate for a 6 ft. man weighing 175 lb. ($12\frac{1}{2}$ stone). The metal parts were covered with rubber foam. The limbs were articulated at hips, knees, shoulders and elbows by $\frac{1}{4}$ inch mild steel tongue and groove joints, swivelling on $\frac{1}{2}$ inch mild steel bolts. There were cavities in the chest compartment and abdomen for accelerometers.

The dummies were dressed in worn service uniform: khaki shirt, battledress, socks and boots. This was specified because clothing obviously influences the drag coefficient of man exposed to the blast wave. It has been reported that clothing was torn away completely from survivors at Hiroshima and Nagasaki.

The effects of the forces acting on the dummies were followed by estimating the displacement of the dummies, and from accelerometer and cinematograph records where these were available. Since the effects would depend upon friction and upon the area exposed to the weapon, six postures were chosen. Standing, crouching and lying were selected as representing three stages in evasive action. Each of these positions was duplicated, facing (or head towards), and sideways-on to the weapon. Each of these six postures was exposed at five ranges, as shown in Table 1 below. The presented areas of the dummies are given in Table 2.

TABLE 1

Layout of Dummies Clad in Battledress

Site No.	Range from G.Z. ft.	Posture of Dummy					
		Prone		Crouching		Standing	
		Facing	Sideways	Facing	Sideways	Facing	Sideways
1	1840	+	+				
2	2056	+	+				
3	2200	+	+	+	+		
4	2390	+	+	+	+	+	+
5	2656	+	+	+	+	+	+
6	3110			+	+	+	+
7	3900			+	+	+	+
8	6000					+	+

TABLE 2

Areas presented by the dummies towards the explosion

Posture	Area in square feet: Facing explosion	Sideways-on
Prone	1	5
Crouching	4	5
Standing	10	5

Results

The results in terms of displacements of the dummies, together with the estimated pressures which occurred at the various ranges are given in Table 3.

TABLE 3

Displacements Classified According to Drag Pressure
Posture and Orientation

Range from G.Z. ft.	Drag Pressure p.s.i.	Over-pressure p.s.i.	Posture					
			Prone		Crouching		Standing	
			F ft.	S ft.	F ft.	S ft.	F ft.	S ft.
1840	7.4	18†	42	66	-	-	-	-
2056	4.4	14.5	2.5	69	-	-	-	-
2200	3.7	12	2	20	15	39	-	-
2390	2.7	10	1	8*	16	18	35	20
2656	1.9	8.5	1	24	9	9	30	16
3110	1	6.4	-	-	6	9	16	10
3900	0.43	4.3	-	-	1	3(4)	4(7)	3(6)
6000	0.11	2.4	-	-	-	-	2(5)	0

*This dummy was sited on firm rocky ground. All others were sited on soft ground.

†Multiple peaks in overpressure record.

In certain cases in Table 3 additional information is given in parenthesis: these figures represent the actual displacements of the centres of gravity, which were corrected for displacement through the final toppling over from the standing or crouching position.

Electrical circuit failure prevented time resolution of accelerometer records and only peak accelerations in the vertical, lateral and longitudinal planes became available for analysis. The peak accelerations in the plane of initial displacements for the instrumented dummies are shown in Table 4.

TABLE 4.

Maximal Positive Accelerations Recorded in the Planes of Initial Displacement of the Dummy Men Exposed in the Open

Range feet	Posture and Plane					
	Prone		Crouching		Standing	
	Facing Vertical g	Sideways Lateral g	Facing Vertical g	Sideways Lateral g	Facing Longitudinal g	Sideways Lateral g
1840	14	14				
2200	9	12	7	19		
2390					26	24
2656	4	7	11	13		
3110					*	55
3900			6	7		
6000					13	3

*Burned out.

It was presumed that the maximum decelerations recorded occurred at the terminal collision with the ground. These results should give some indication of the damage sustained, and are quoted in Table 5.

TABLE 5

Maximal Decelerations Derived from Accelerometer Results Classified According to Range Posture and Orientation

Range Feet	Posture					
	Prone		Crouching		Standing	
	Facing g	Sideways g	Facing g	Sideways g	Facing g	Sideways g
1840	18	35				
2200	18	17	17	15		
2390					53	11
2656	12	17	26	11		
3110					*	22
3900			0	26		
6000					16	5

*Burned out.

Records were also made of joint changes and displacement of steel helmets.

It is noted from Table 3 that for any drag pressure, the displacement of the dummies oriented sideways-on is of the same order, irrespective of posture. This implies that friction with the ground did not impede take-off of the prone and crouching dummies.

From (i) the drag pressure, (ii) the surface area presented to the explosion, and (iii) the duration of the blast wind, it is possible to calculate impulse. This is proportional to the product of (i) x (ii) x (iii).

Using the figures for presented area given in Table 2 above, together with data for drag pressures and wind durations, a curve for the relationship between impulse and displacement has been constructed. Figure 1 shows this relationship. This solid line is the regression curve calculated to fit the results. It has the form:-

$$\text{displacement (feet)} = \left(\frac{A \times P \times T}{1660}\right)^{1.5}$$

where A = presented area (in^2)

P = peak drag pressure (p.s.i.),

T = duration of positive phase (sec.)

The dotted lines in Figure 1 show the 95% confidence limits based on the fore-going data.

Regarding the accelerometer data, there was firm correlation between initial acceleration recorded and the displacement suffered. The correlation between displacement and maximal decelerations is poor, and no

correlation can be recognized between deceleration and severity of damage to the dummy. It is apparent therefore that while some displacement must occur to cause injury, injury or damage depends more upon the detailed nature of the terminal collision than upon the magnitude of the displacement or rapidity of deceleration.

Conclusions

In attempting to deduce what would have been the fate of soldiers exposed in the same way as the dummies the authors of Reference (2) conclude that:-

(1) All such soldiers would have suffered severe flash burns on exposed skin.

(2) All such soldiers within 3500 ft. (i.e. Sites No.1-6) would have suffered serious, lethal, radiation illness.

(3) All soldiers beyond 4000 ft. in open country would have suffered little or no injury from blast displacement per se.

(4) Soldiers at ranges of less than 2250 ft. would probably have suffered moderate to very severe injuries from blast displacement per se. (Three metal limbs were disarticulated in this zone).

(5) The severity of injury would have been roughly proportional to the surface area presented to the blast wave. Thus crouching and standing dummies show greater displacement than prone dummies at similar ranges. Similarly prone dummies exposed sideways-on to the explosion suffered greater displacement than prone dummies with heads towards Ground Zero.

In view of the observed displacement of steel helmets it is further concluded that wearing the retaining strap of a steel helmet under the chin is inadvisable, and that steel helmets might possibly become dangerous missiles, especially in confined spaces.

Some further trials with dummy men were performed at Operation Antler and are fully reported in Reference (6). These trials were carried out out for Antler Round 2 (about 5 KT) and Round 3 (about 25 KT) on similar lines to the tests at Buffalo, although in the Antler tests some additional dummies were exposed in Daimler Scout Cars (Round 2) and Champ Vehicles (Round 3). The following conclusions are given:-

(a) The information obtained on the displacement of dummies by blast confirms and amplifies that obtained from Operation Buffalo.

(b) Damage to dummies was more severe in the area affected by the precursor blast wave of the balloon burst weapon of about 25 KT total yield, than would have been expected from results at similar peak static overpressures obtained from the tower burst weapon of about 5 KT total yield where no precursor was present. (It should be remembered that precursor conditions only occur when the blast is likely to be very severe in any case).

(c) The conclusion reached after Operation Buffalo, that the best position for a man caught in the open when struck by a blast wave is prone and facing the blast, was confirmed.

9.3. Light Earth Covered Structures and Earthworks

9.3.1. Light earth-covered surface shelters and shallow buried shelters

Air blast is the controlling damage parameter for light earth-covered surface structures, and also for light shallow buried underground structures. Earth cover provides structures with substantial protection against air blast damage as well as against thermal and nuclear radiation. More protection against missiles is also provided by earth cover.

Earth-covered surface shelters - An earth mound reduces the blast reflection factor and improves the aerodynamic shape of the structure. This results in a large reduction in both horizontal and vertical translation of forces. It is estimated that the peak force applied to the structural elements is reduced by a factor of at least two by the addition of earth cover. The structure is somewhat stiffened against large deflections by the buttressing action of the soil when the building is sufficiently flexible.

Shallow-buried underground structures - For depths of cover less than 8 ft., in most soils there is little attenuation of pressure applied to the horizontal, top surface of an underground structure. No increase in pressure exerted on the structure appears to arise from ground shock reflection at the interface between the earth and the structure, partially accounting for the factor of two reduction in peak force mentioned above. The lateral pressures exerted on vertical faces of a buried structure have been found to vary from about 15% of the pressures on the roof in dry, well compacted silty soil to approaching 100% in a porous saturated soil. The pressures exerted on the bottom of a buried structure in which the bottom slab is a structural unit integral with the walls, may be between 75% and 100% of the pressure on the roof.

Damage calculations - The peak overpressure curves for the appropriate air or underground burst conditions may be used to predict damage to relatively shallow buried underground structures located more than two crater radii from the burst point. For most of these structures the response time and the period of the structural elements is short, and the damage criteria given in Table I apply for all yields. For structures with long response times, a separate analysis must be made considering the structural characteristics and the weapon yield.

TABLE I - Damage Criteria for Light Earth Covered Structures

Structure	Damage	Peak Over-pressures (psi)	Remarks
Light steel arch surface shelter with 3 ft. of earth cover over crown. (10-0.141 inch gauge corrugated steel with a span of 20 to 25 ft.)	(Severe	25-35	Collapse
	(Moderate	20-25	Slight permanent deformation of arch
	(Light	10-15	Deformation of end walls, possible entrance-door damage.
Light reinforced concrete surface or underground shelter with 3 ft. minimum earth cover (2 to 3 inch thick panels with beams spaced at 4 ft. centres).	(Severe	25-35	Collapse
	(Moderate	15-30	Deformation, severe cracking and spalling of panels
	(Light	10-15	Cracking of panels, possible entrance door damage

Note. - A spread in peak overpressures for various degrees of damage is indicated to allow for differences in structural design, soil conditions, shape of earth mound, and orientation with respect to the blast wave. For defensive planning use the lower values.

9.3.2. Field Fortifications and Defences - Air blast is the controlling damage parameter for destruction of field fortifications such as unreinforced trenches and foxholes, revetted positions, and covered field shelters.

Un-reinforced Fortifications - The resistance of unrevetted trenches and foxholes to air blast is primarily dependent upon the soil characteristics, particularly the cohesive qualities of the soil.

Revetments - Revetted emplacements resist collapse at considerably greater overpressures than unrevetted emplacements. Light revetting materials such as chicken wire and burlap, or paste board, corrugated sheet metal, or plywood, when well supported, are fairly resistant to air blast. Light timber revetments are more resistant to air blast.

Overhead Cover - Covered fortifications that have their cover flush with ground level are subject primarily to downward pressures on the roof, whereas those fortifications having their cover above ground level are subjected also to drag loading,which tends to remove loose earth and disarrange and remove the cover structures. Entrances are usually the weakest point of blast resistance.

Other Damage Mechanisms - Severe air blast damage to revetted field fortifications occurs at ranges where damage due to direct ground shock and cratering alone is insignificant. However, for unrevetted foxholes and trenches in most soils, the direct ground shock produced by an underground burst contributes somewhat to the collapse. Superficial scorching of the wooden portions of field fortifications may also occur.

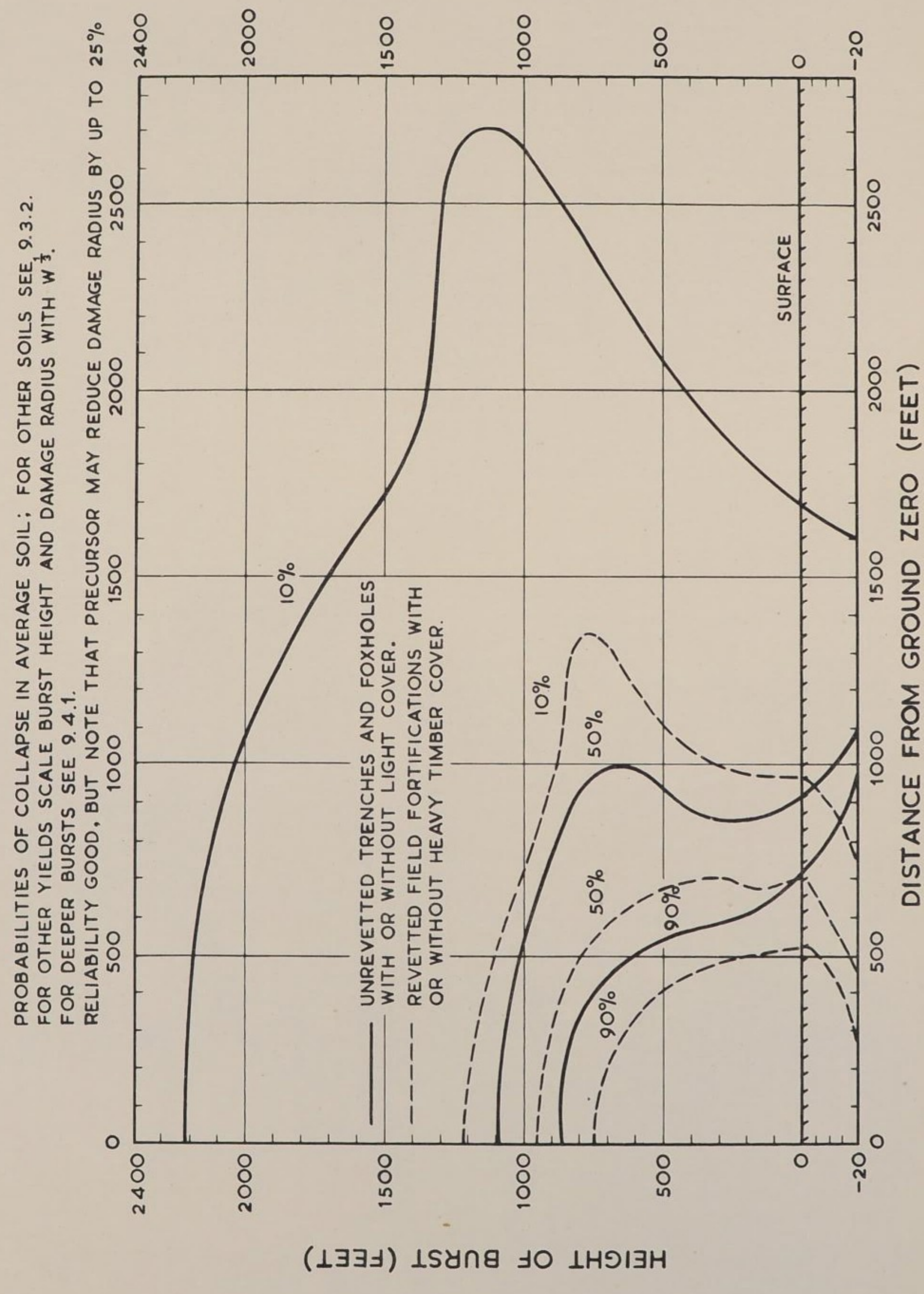
Damage Computations - The criteria for air blast damage are given as probabilities of causing collapse of the fortification. Figure 1 gives the height of burst versus ground range from a 1 KT burst for damage in average soil to unrevetted trenches and foxholes with or without light cover, and rivetted field fortifications with or without heavy timber cover. The given damage ranges are reduced in cohesive soils and increased in cohesion soils. If a precursor is expected, ranges may be as much as 25% less than those shown.

To obtain heights of burst and distances for yields other than 1 KT, use the scaling law -

$$\frac{d_1}{d_2} = \frac{W_1^{\frac{1}{3}}}{W_2^{\frac{1}{3}}} = \frac{h_1}{h_2}$$

Where d_1 and h_1 are ground distance and height of burst for yield W_1 KT and d_2 and h_2 are ground distance and height of burst for yield W_2 KT.

NOTE: For damage to barbed wire defences see Section 9.4.1.



DAMAGE TO FIELD DEFENCES. 1 KT.

9.4. Military Field Equipment

9.4.1. Introduction

Damage Mechanisms - Military field equipment targets are for the most part small, rugged, and free to move, and as such are primarily sensitive to the drag forces associated with the blast wave. Under some circumstances however, such as when items are shielded from drag forces or lie in the early regular reflection region, crushing by peak blast wave overpressures may be important. The drag forces tend to displace and to tumble targets of this type, and in the process, to damage them. Direct thermal damage to field equipment in general is not of importance; however, for certain items such as POL dumps, fire effects are important and are treated below. Secondary fire hazards from vegetation are not considered in this section.

Damage levels and definitions - Many factors must be considered in the selection of damage criteria for military field equipment targets. Among these are orientation of the item of equipment with respect to ground zero, orientation of the blast wave with respect to surface, i.e. whether the item is in the regular or in the Mach. region; shielding effects; the nature of the particulate matter in the blast wave; the presence or lack of flammable materials; the magnitude of the blast forces.

To simplify the presentation of damage criteria for blast effects in the following paragraphs, a height of burst versus ground range method of presentation for various levels of damage is used. The levels of damage are defined as follows:-

Severe that damage which is sufficient to prevent the accomplishment of any useful military function and the repair of which is essentially important without removal to a major repair facility.

Moderate that damage which is sufficient to prevent any military use until some repairs are effected.

Light that damage which does not seriously interfere with immediate military operations but necessitates some repair to restore the item to complete military usefulness.

Damage Probabilities - Specific examples of the types of damage associated with a given level of damage are included for each major item of equipment. Distances shown for moderate damage are the distances for which the probability of the damage occurring is 50%, and in some cases where the data permits, 10%. Distances shown for severe damage are those for which the probability of damage occurring is 50%, and in some cases where sufficient data is available, 90% and 10%. For light damage the distances are those for which the probability of damage is 10%. It is intended that the light damage curve and the moderate curve for 10% probability should be used to indicate approximate limits of damage, and thus may be of value in determining how close equipment may be placed to friendly bursts without endangering the combat usefulness of that equipment. It is assumed that for all damage curves, unless stated otherwise, that the items of equipment are oriented in a random fashion with respect to ground zero and lie unshielded on fairly level terrain. A discussion on shielding effects is given below.

Terrain and Topographrical Effects - The damage curves presented are the result of a great many exposures of military equipment to full-scale tests, and it is believed that the reliability of the data for a great variety of terrains is excellent. However, for bombs which are expected to produce a precursor over a terrain which yields no dust, the distances at which a given level of damage occurs may be somewhat less than indicated. Until further evidence is available however, it is recommended that the criteria shown be used for all types of surface.

Local topography may have considerable effect on the characteristics of the blast wave. In general, these result in an increase in damage for military field equipment located on the side of a hill facing towards the blast, and a decrease in damage for equipment located on the side facing away from the blast, compared with the damage at the same range on level terrain. No quantitative statement can be made at present as to the accentuation on the front face or the decrease on the rear face. However, the modifications may be so great that offensively, if more targets are located on the rear slope of a hill with respect to a proposed burst point, serious consideration should be given to re-selecting the intended ground zero. Defensively, every advantage should be taken of natural terrain features which provide drag shielding for items of our own equipment.

Effects of 'digging in' The damage curves for military equipment are drawn for equipment in the open on fairly level terrain, fully exposed to the drag forces of the blast wave. By 'digging in' military equipment, the equipment is somewhat shielded from these drag forces. The amount of shielding depends upon the type of emplacement used for the item of interest. For example, a shallow, open pit as an emplacement for an artillery piece provides little drag shielding, whereas a deep pit provides much more effective shielding. In the former case, the damage curves as presented could be used for predicting damage. In the latter case however, the damage curves predict, for a given level of damage, distances much greater than those which would actually be experienced. In order to make estimates of the effects of drag shielding, the following rule should be used:- "For items of military equipment which are well dug in, reduce the severe damage level by 2, and the moderate level by 1, i.e. both Severe and Moderate damage become Light."

Severe damage extends to ground ranges up to 50% less than those shown for the original severe damage curve. 'Well dug in' implies that the item is completely below the surface, without overhead cover.

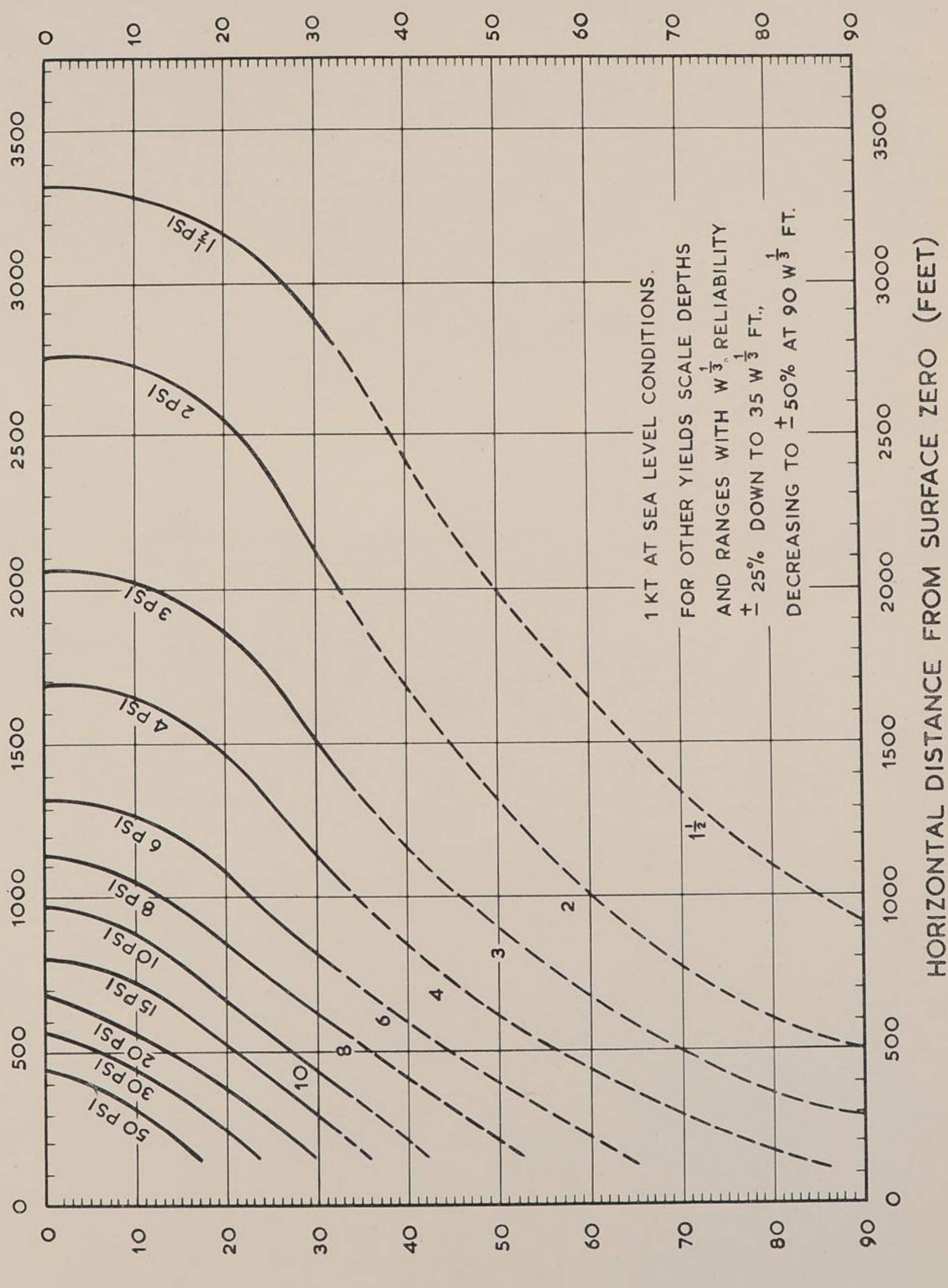
Sub Surface Bursts - It is to be noted that all damage curves of this section extend upwards from zero height of burst. To determine the distance to which a given item of equipment suffers a given level of damage from a sub surface burst, the curves of Figure 1 may be used. It is necessary to determine which curve (isopressure contour) of Figure 1 for a zero depth of burst, meets most closely the zero height of burst intercept of the damage curve of interest. This isopressure contour then serves as a continuation of the damage curve to determine distances for sub surface bursts. An example of this procedure is found accompanying Section 9.4.5, Figure 1.

Scaling - The scaling laws given with the damage curves of this Section have been checked for items of military equipment over a wide range of yields. It is believed that the laws are valid over a range of yields from 0.1 KT to 100 MT.

Other types of equipment - Criteria for many items of military field equipment not specifically mentioned in this Section can be determined by an examination of the damage curves that are presented. For example, heavy engineering heavy equipment such as bulldozers, graders, cranes and shovels are probably less vulnerable than a truck but more so than a tank. Therefore a reasonable estimate of the distance to which some items may be damaged can be arrived at by taking a mid-range value between that for trucks and that for tanks. Many types of military equipment are omitted; however, they may frequently be associated with other items of equipment that are specifically mentioned in the preceding paragraphs. An example of this is the pumping equipment normally associated with a POL dump.

Wire entanglements are very variable in vulnerability because of the many factors involved, such as the nature of the soil, the quality of the workmanship, and the depth of the picketing. For average soil conditions and U.S. military standards of construction, it has been determined that the criteria given in Section 9.4.4, Figure 1, can be used for estimating the distance to which it can be expected that wire entanglements are torn from their picketing or other supports. For double apron barbed wire fences use the telephone and switchboard curve of the above figure, and for concertina entanglements use the radio and electronic fire control instrument curve of the same figure.

Tents. Because of the large variability in anchorage, no definite criteria can be given. They are however, likely to fail in most cases at overpressures between 0.5 and 3 p.s.i.



DAMAGE RADIUS REDUCTIONS
FOR UNDERGROUND BURSTS

9.4.2. Tanks, Armoured Vehicles, Artillery, Ordnance Items, etc. - Tanks and artillery are about equally vulnerable except in the light damage category. Table I indicates which set of curves best fits the experimental data for other items of military ordnance. Examples are also given of damage levels for the various items. In all cases scaling to other yields is with $W^{\frac{1}{3}}$ for height of burst. and with $W^{0.4}$ for damage distances. Note that the curves apply to light and heavy vehicles; light, medium and heavy artillery; and light, medium and heavy tanks. The artillery curves include anti-aircraft artillery except for the electronic fire control equipment, which is discussed in Section 9.4.4. Thermal damage to ordnance equipment is generally superficial, such as scorching of paint and tyres. Canvas covers may be ignited from thermal radiation at energies ranging from 15 - 50 calories per sq. c.m. from a 1 KT burst, depending on composition, weight, impregnation, etc.

TABLE I - DAMAGE TO ORDNANCE ITEMS

Item	Damage Curves Most Closely Related	Examples of Severe Moderate and Light Damage
Tanks, all types	Sect.9.4.2. Fig.1	S- extensive turret, main armament and track damage - possible dismemberment. M- overturning, track and turret damage. L- antenna damage.
Artillery	Sect.9.4.2. Fig.1.	S- extensive recoil mechanism, wheel and trail damage, possible dismemberment. M- bent and twisted trails, some recoil mechanism danage, wheels may be torn off. L- sight glass breakage.
Mortars and recoil-less rifles	Sect.9.4.2. Fig.1 (for light damage use artillery curve)	S- Dismemberment. M - Twisted standards and mountings L- Sight breakage
Small arms and machine guns	Sect.9.4.2. Fig.1 (for light damage use artillery curve)	S- Dismemberment. M - Broken stocks, twisted and broken mountings. L - Cracked stocks
Rocket launchers	Sect.9.5.3. Fig.1	S-Torn to pieces. M - Twisted tube. L-Sight damage
LVT's and DUKW's (on land)	Sect.9.5.3. Fig.1	S- Great distortion and possible rupture of hull. M - Hull distortion, track damage. L - Glass breakage

9.4.3. Land Mines and Minefields Among the many parameters determining the effects of atomic detonations on minefields are type of mine, soil characteristics, mine spacing and depth of burial, and the characteristics of the blast wave. Methods of accounting for all of these parameters are not available for all types of mine. However, information is available on a number of mine types from which generalised criteria have been developed. Because mines are insensitive to thermal and nuclear radiation these effects are not treated in the discussion which follows.

Depth of Burial and Soil Type - In general, if the soil is not frozen and the depth of burial is not greater than about 2 ft., the criteria as given below are applicable for most soils normally encountered. There is at present no information available on the transmission of pressure through frozen soils, but it is believed that if the soil is frozen, no detonation of buried mines can be depended upon except in the region of cratering.

Sympatheric Detonation - Mines are usually spaced so that the pressures from the detonation of one mine do not sympathetically detonate adjacent mines. However, the additional overpressures in the blast wave from an atomic detonation may be sufficient to cause some sympathetic detonation if the spacing of the mines is close enough to be critical. Sufficiently large gaps in minefields halt this process, so that extensive clearance by sympathetic detonation cannot be depended upon. The criteria as given below do not include any sympathetic detonation effects.

Blast Wave Form - In general, land mines are sensitive to the rise time of the blast wave, i.e. if the rise time is long, greater pressures are needed to detonate a given mine than if the rise times are short. Long rise times are characteristic of the precursor zone. Therefore, in the criteria given below, two sets of data must be specified for each mine type depending upon whether or not the mine is expected to be in a precursor zone. For all bursts for pressures less than about 8 p.s.i. the criteria are the same for bursts which produce a precursor as for those which do not. This is also true for mines with fuzes which are insensitive to rise times.

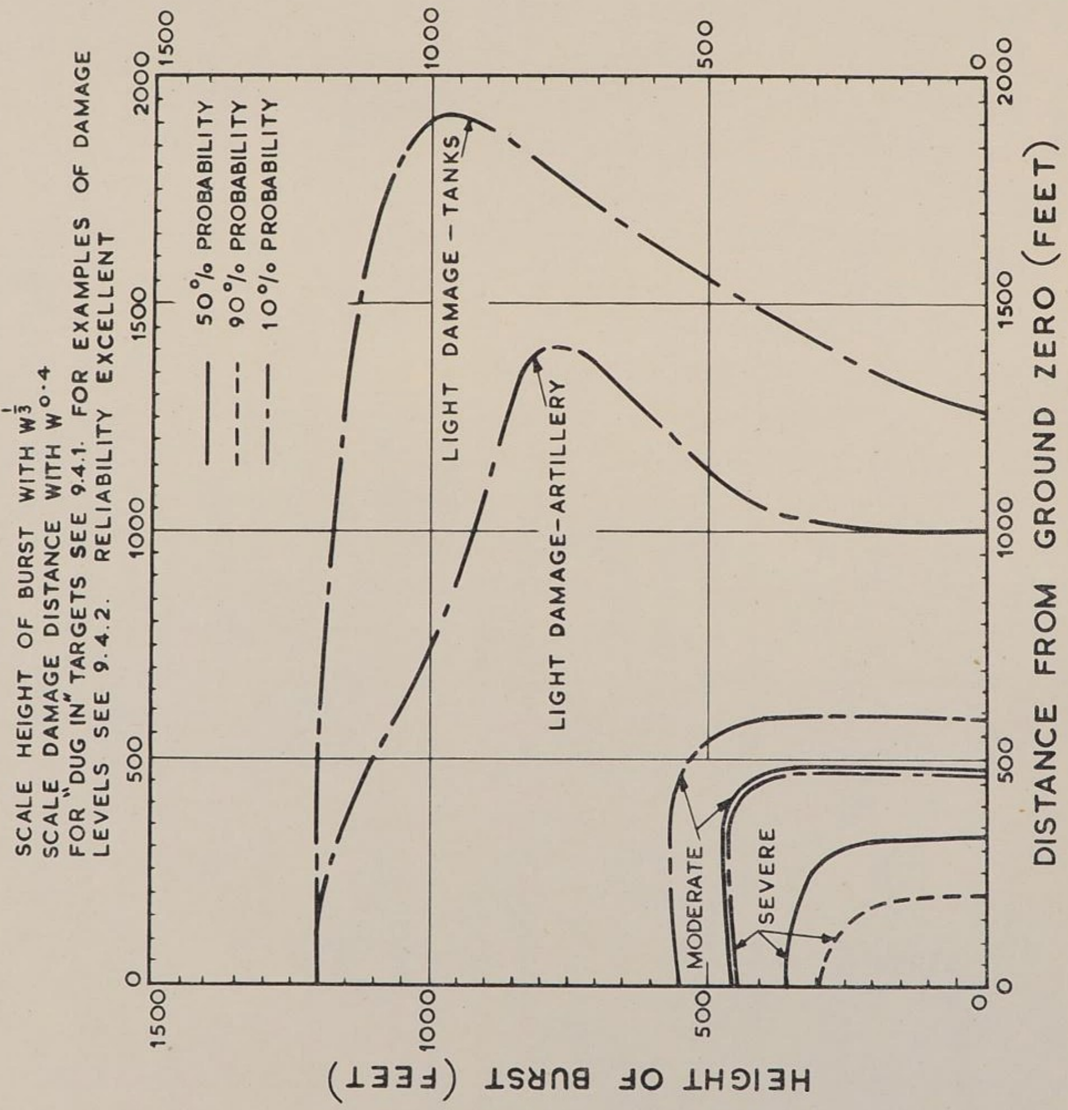
Mine Type - Although mines can be detonated by explosions acting on either the main explosive or on the more sensitive primer or boost, the overpressures required are so high that blast action on the pressure plates always controls. Detonation criteria presented in Table I are based on interpolation of test results on fuzed mines of the pressure-plate type. The Table does not apply to unfuzed mines, or to other mine types such as those with prong type fuzes or with double pressure activated pressure plates.

Criteria - In Table I are listed mines of various nations. For each mine criteria are given for 90% and for 10% detonations for precursor and non-precursor type blast waves, for depths of burial from 0" - 12" and from 12" - 24". Criteria for 50% probability of mine detonation are not given, since mine problems are concerned either with substantially complete clearance (90% probability), or with substantially little effect on the field (10% probability). Data of Table I are measured in the case of American mines, computed for the remainder. This Table is to be used in conjunction with the usual height of burst pressure curves for the appropriate surface conditons, the usual pressure scaling laws for yield being applicable.

TABLE I - Overpressures in p.s.i. Required to Detonate Various Mines

Country	Mine	0"-12" Depth of Burial				12"-24" Depth of Burial			
		Percent detonations - 90%		10%		90%		10%	
		Rise Time		Rise Time		Rise Time		Rise Time	
		Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow
Belgium	PRB ND-49 Heavy Model A/T	20	30	17	25	30	30	25	25
	PRB ND-49 Light Model A/T	20	30	17	25	30	30	25	25
France	Model 1947 A/T	3	3	(*)	(*)	5	5	1.5	1.5
	Model 1948 A/T	15	20	10	15	20	20	15	15
	Model 1948 Plate Charge offset pressure	4	4	1.5	1.5	6	6	2	2
	Model 1951 Undetectable buried spider plate	5	5	2	2	7	7	3	3
	Model 1951 Shaped Charge, steel, offset pressure	4	4	1.5	1.5	6	6	2	2
	Model 1951 Shaped Charge, bakelite offset pressure	10	15	8	12	15	15	12	12
	Model 1948 A/P	4	4	1.5	1.5	6	6	2	2
Germany	TMi-35 A/T	4	4	1.5	1.5	6	6	2	2
	TMi-35 Steel A/T	4	4	1.5	1.5	6	6	2	2
	RMi-42 A/T	17	25	15	20	25	25	20	20
	SCHU A/P	2	2	(*)	(*)	3	3	(*)	(*)
Italy	CS 42/2 A/T	4	4	1.5	1.5	6	6	2	2
	CS 42/3 A/T	4	4	1.5	1.5	6	6	2	2
	CC 48 Shaped Charge A/T	7	7	3	3	9	9	5	5
	P-1 A/T	12	18	9	14	18	18	14	14
	P-2 A/T	12	18	9	14	18	18	14	14
	R A/P	2	2	(*)	(*)	3	3	(*)	(*)
	RM A/P	2	2	(*)	(*)	3	3	(*)	(*)
Turkey	4.4 A/T	7	7	3	3	9	9	5	5
	9.9 A/T	4	4	1.5	1.5	6	6	2	2
U.K.	Mark V (HC) - Buried Spider Plate	10	15	7	11	15	15	11	11
	Mark V (GS) - Buried Spider Plate	10	15	7	11	15	15	11	11
	No.5 Mk. 1 A/P	3	3	(*)	(*)	5	5	1.5	1.5
	No.75 Mk.II	7	7	3	3	9	9	5	5
U.S.A.	M-6 A/T	10	15	7	11	15	15	11	11
	M-7 A/T	35	35	30	30	35	35	30	30
	M-15 A/T	10	15	7	11	15	15	11	11
	M-14 A/P	7	7	3	3	9	9	5	5
	T-18 A/T	10	15	8	12	15	15	12	12
	T-20 A/P	3	3	(*)	(*)	5	5	1.5	1.5
U.S.S.R.	YAM-5 A/T	15	15	11	11	15	15	11	11
	YAM-5K A/T	14	14	10	10	14	14	10	10
	YAM-5M A/T	16	16	12	12	16	16	12	12
	YAM-5U A/T	15	15	11	11	15	15	11	11
	TMS-B A/T	5	5	3	3	8	8	4	4
	TMD-B A/T	15	15	11	11	15	15	11	11
	TM-41 A/T	25	35	20	30	35	35	30	30
	PMP-6 A/P	2	2	(*)	(*)	3	3	(*)	(*)
	PMD-7 A/P	2	2	(*)	(*)	3	3	(*)	(*)

* These mines may detonate in significant percentages at very low pressures (i.e. less than 1.5 p.s.i.



DAMAGE TO TANKS, FIELD ARTILLERY, ETC. 1K.T.

9.4.4 Signals and Electronic Equipment Including Field Radar - As the heat sensitive components of communications and electronic fire control equipment are generally shielded by the casings from thermal radiation, blast effects usually override thermal effects in cases where thermal effects alone might otherwise be significant. Radios, telephones, switchboards and electronic fire control equipment are very susceptible to damage by displacement. Figure 1 indicates the range at which damage is expected for these types of equipment. The curves are constructed on the assumption that the items of interest are unshielded from the effects of the blast wave and that the equipment is not intimately associated with other larger items. For example, a radio mounted in a truck is severely damaged if the truck is severely or moderately damaged, and a large switchboard installed in a building is severely damaged if the building collapses. Thus, if the equipment is intimately associated with other equipment, or with a structure, the criteria for damage to the other equipment or to the structure, should be used to determine the damage to the communication equipment. Note that only severe damage is indicated in Figure 1. Light damage for portable field radios consists of aerial damage, which is the basis for the tank light damage curve of Section 9.4.2.

Poled Telephone Routes - For estimating damage to telephone poles connected with wire, use Figure 2 (a) for arrays extending radially from ground zero, and Figure 2(b) in the case of transverse pole line arrays. Wire on poles is likely to be destroyed by the blast wave out to the limit of pole breakage. However, blast damage to wire on poles cannot be depended upon at greater distances.

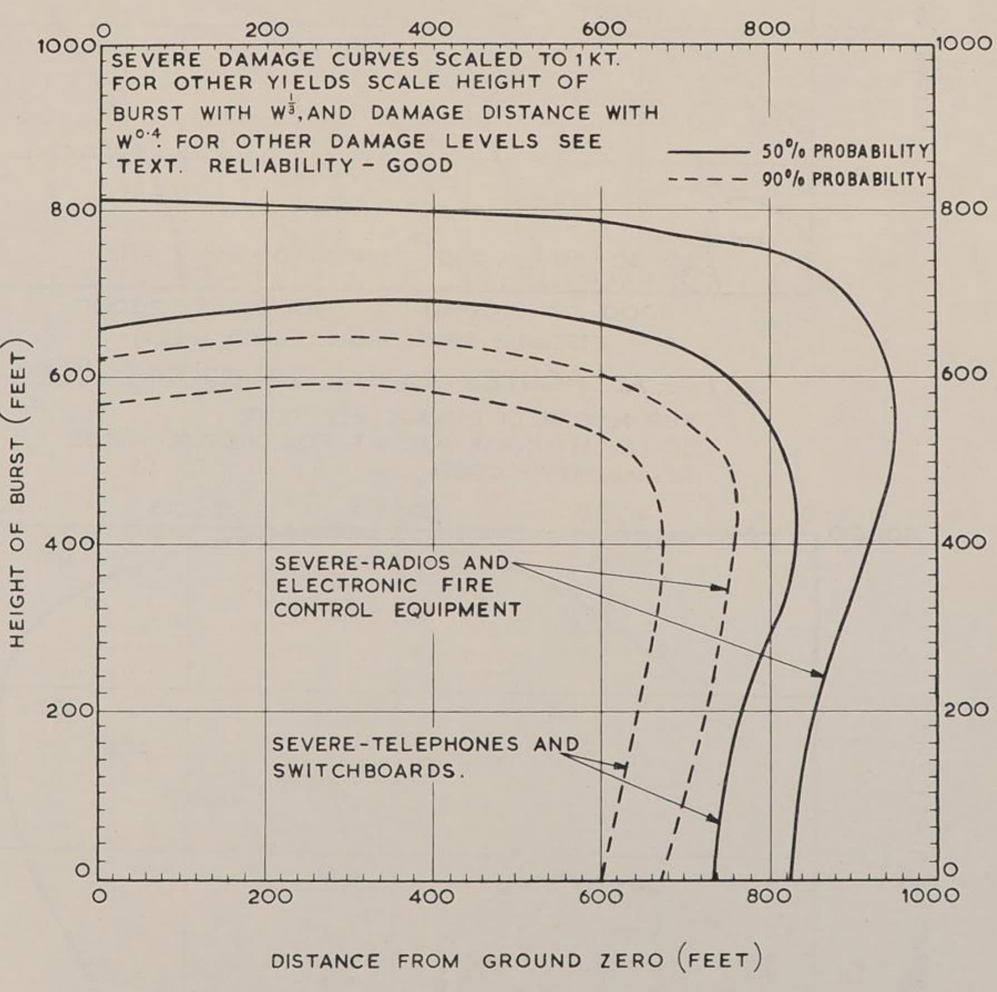
Scaling Laws - Scaling of damage distances for bursts of different heights and yields, in the case of Figure 1, follows the usual $W^{\frac{1}{3}}$ scaling for height of burst, and $W^{0.4}$ scaling for damage distance, i.e.

$$\frac{h_1}{h_2} = \frac{W_1^{\frac{1}{3}}}{W_2^{\frac{1}{3}}} \quad \text{and} \quad \frac{d_1}{d_2} = \frac{W_1^{0.4}}{W_2^{0.4}}$$

Where h_1 = height of burst d_1 = damage distance for yield W_1

and h_2 = " " d_2 " " " " W_2

In the case of the poled telephone route data in Figures 2(a) and 2(b) there is of course, no need for scaling for yields below 1 MT, as values may be read directly from the curves, or by interpolation of iso-yield contours through the given intermediate points. For yields above 1 MT, scale both height of burst and damage distance with $W^{\frac{1}{3}}$ from the 1 MT curve.



DAMAGE TO SIGNALS AND ELECTRONIC EQUIPMENT

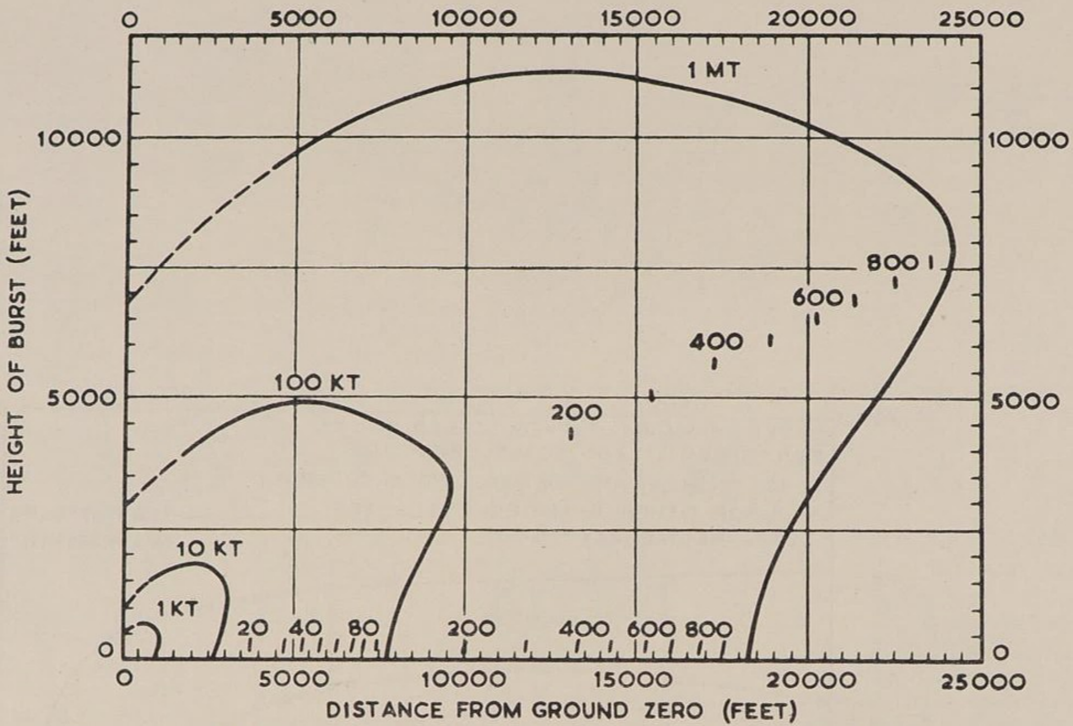


FIG. A. ROUTES RADIAL TO GROUND ZERO

FOR NATURE OF DAMAGE SEE TEXT.
SCALE 1 MT CURVE WITH $W^{\frac{1}{3}}$ FOR GREATER YIELDS.
RELIABILITY – GOOD

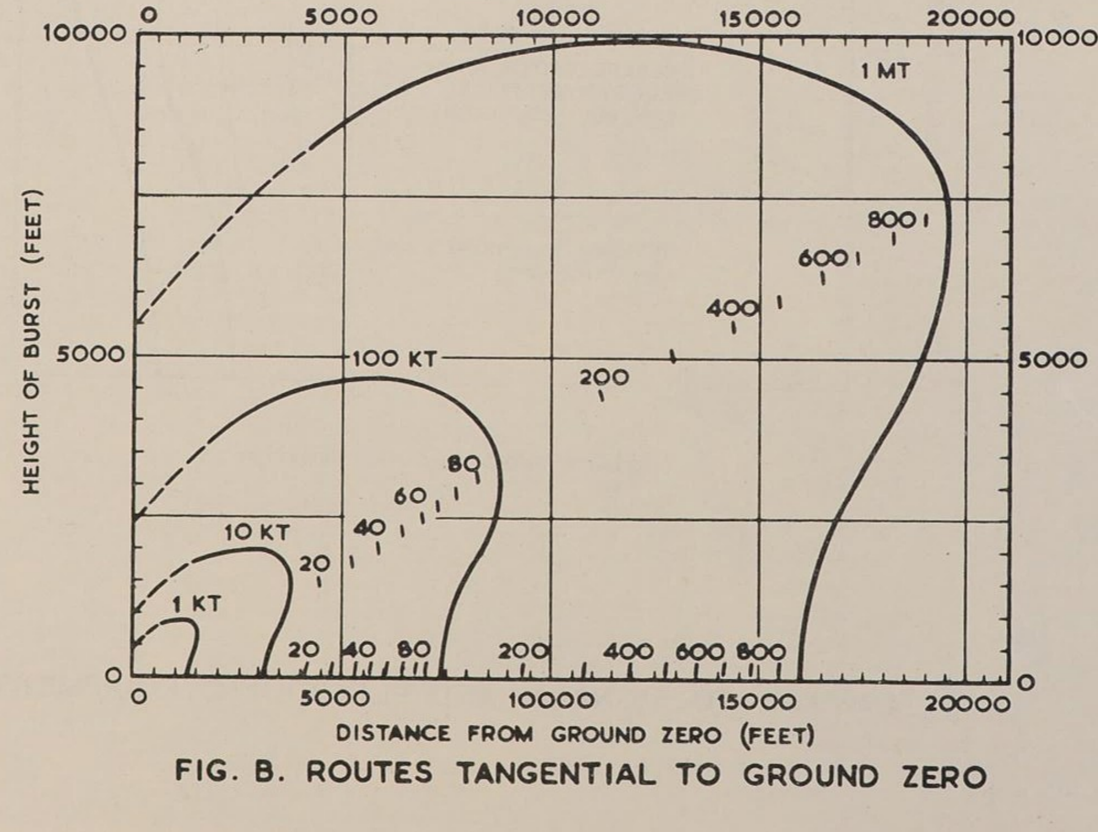


FIG. B. ROUTES TANGENTIAL TO GROUND ZERO

DAMAGE TO POLED TELEPHONE ROUTES

9.4.5. Supply Dumps - Height of burst curves are given in Figure 1 for blast damage to POL stored in 5 or 55 gallon drums (U.S. gallons), ammunition and rations in their standard packaging and other items normally packaged in small containers. The damage indicated refers to the packaging, and is caused by crushing, or by violent displacement and resultant tumbling, of the dump items. For POL, rupture of the packaging results in loss of the contents. However, this may not be the case for other items. Individual rounds of ammunition may be serviceable, even though thrown for great distances. This may also be true for rations. Note that only severe and light damage are indicated. Moderate damage is not considered, because the transition from severe to light damage is so abrupt for this type of target.

Damage Definitions:-

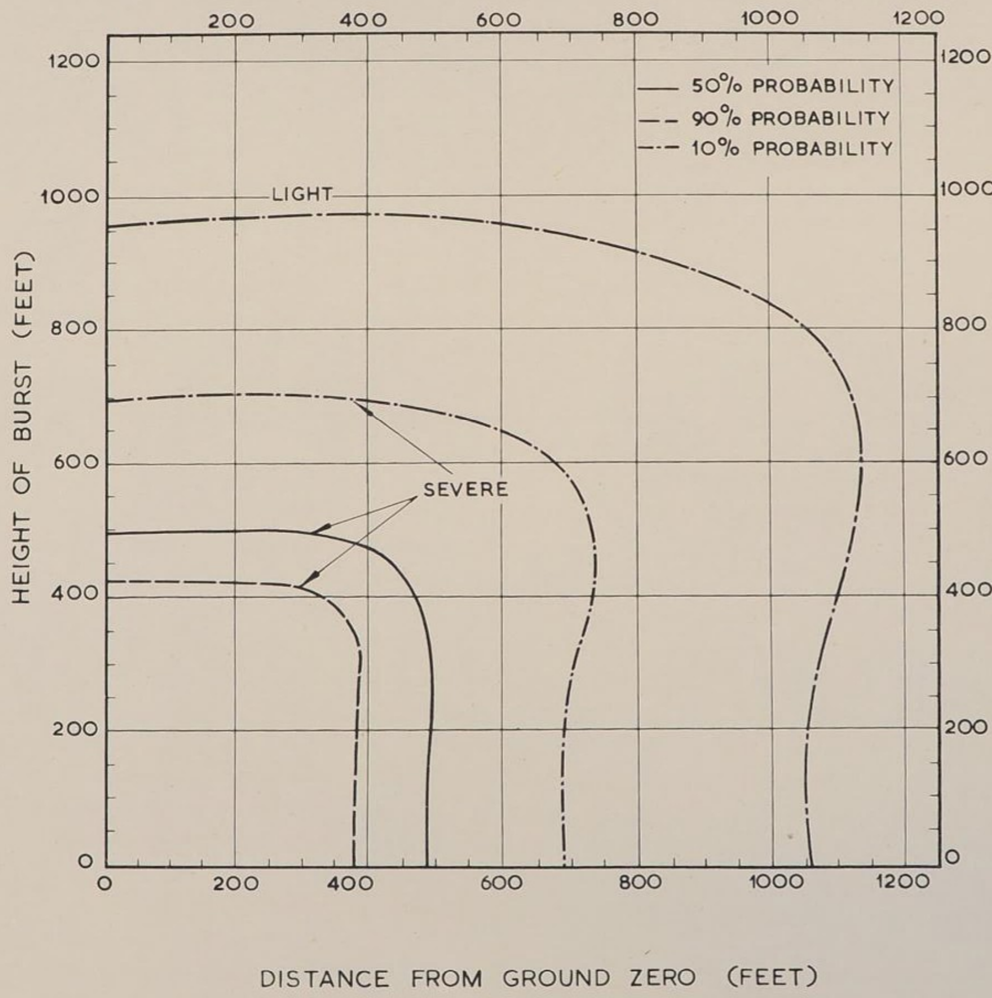
Severe - Rupture of casings, wide scattering, possible destruction of contents.

Light - Scattering of the cases with some cracking and some loss of contents.

Scaling for other yields, heights of burst, and damage distances follows the $W^{\frac{1}{3}}$ rule for height of burst and $W^{0.4}$ for distance, as in the preceeding section.

Thermal Damage - Materials in supply dumps packaged in wooden or metal containers are not significantly affected by thermal radiation. However, serious fires may result in supply dumps from the ignition of kindling fuels such as newspaper, dry weeds and grass, and other litter comprised of thin organic materials. These primary ignitions may lead to fires in less combustible materials in the dumps which otherwise would not ignite. POL dumps are highly susceptible to fire under most conditions, owing to the establishment of ignitions in kindling fuels and the subsequent growth of these ignitions into fires, in either accidentally spilled fuels or in fuels spilled from containers ruptured by the blast. Energies required for ignition of various kindling fuels are given in Part 6, Chapter 5, Table 2. In the absence of kindling fuels it is considered unlikely that POL itself will be ignited, whether in open or closed containers or spilled on the ground.

SCALED TO 1KT. FOR OTHER YIELDS SCALE HEIGHT OF BURST WITH $W^{\frac{1}{3}}$, DAMAGE DISTANCE WITH $W^{0.4}$. FOR "DUG IN" TARGETS OR FOR UNDERGROUND BURSTS SEE 9.4.1.
RELIABILITY - GOOD.



DAMAGE TO SUPPLY DUMPS

9.5. VEHICLES AND ROLLING STOCK

9.5.1. Railway Locomotives - Figure 1 gives iso-damage curves for severe, moderate and light damage to railway locomotives. Separate curves are given for side on and end on orientation at the higher damage levels. End on orientation refers to the blast wave striking the front or rear of the locomotive, and side on orientation refers to the blast wave striking either side of the locomotive. If it is not known what orientation exists, a mid-range between end on and side on values should be used for a given damage level. For surface or sub surface bursts, roadbeds are likely to be completely demolished out to a radius of 1.5 times the crater radius. Air bursts are relatively ineffective against roadbeds. For damage to structures normally associated with a marshalling yard, see Section 9.2. The damage curves of Figure 1 are drawn for a 50% damage probability. Examples of the damage levels used are -

Severe, intensive bending and twisting of end frame with overturning probable;

Moderate, bending or crushing of boiler and side and main rods with overturning possible;

Light, slight crushing of cab and glass breakage.

Scaling to other yields follows $W^{\frac{1}{3}}$ for height of burst and $W^{0.4}$ for damage distance, as in previous sections (e.g. 9.4.4.).

9.5.2. Railway Rolling Stock - Damage criteria for railway rolling stock are given in Figure 1. The rolling stock includes box wagons, tank wagons and open wagons. It is assumed that the wagons are randomly oriented with respect to ground zero, and that they are carrying a normal load. If the blast wave strikes the equipment side on, the damage will be greater than that indicated. If the wagons are empty, they are less vulnerable to vertical loads and more vulnerable to horizontal loads. Examples of the damage levels are,

Severe - extensive distortion, de-railment probable;

Moderate - sides of wagons demolished, some distortion of frame, possible de-railment;

Light - minor damage to sides and doors.

Box wagons moderately damaged could conceivably be used as flat wagons; however, as box wagons they would not be usable without extensive rebuilding. Scaling of Figure 1 for other heights of burst follows the $W^{\frac{1}{3}}$ rule, and for other damage distances, $W^{0.4}$. rule, as in previous sections (e.g. 9.4.4.)

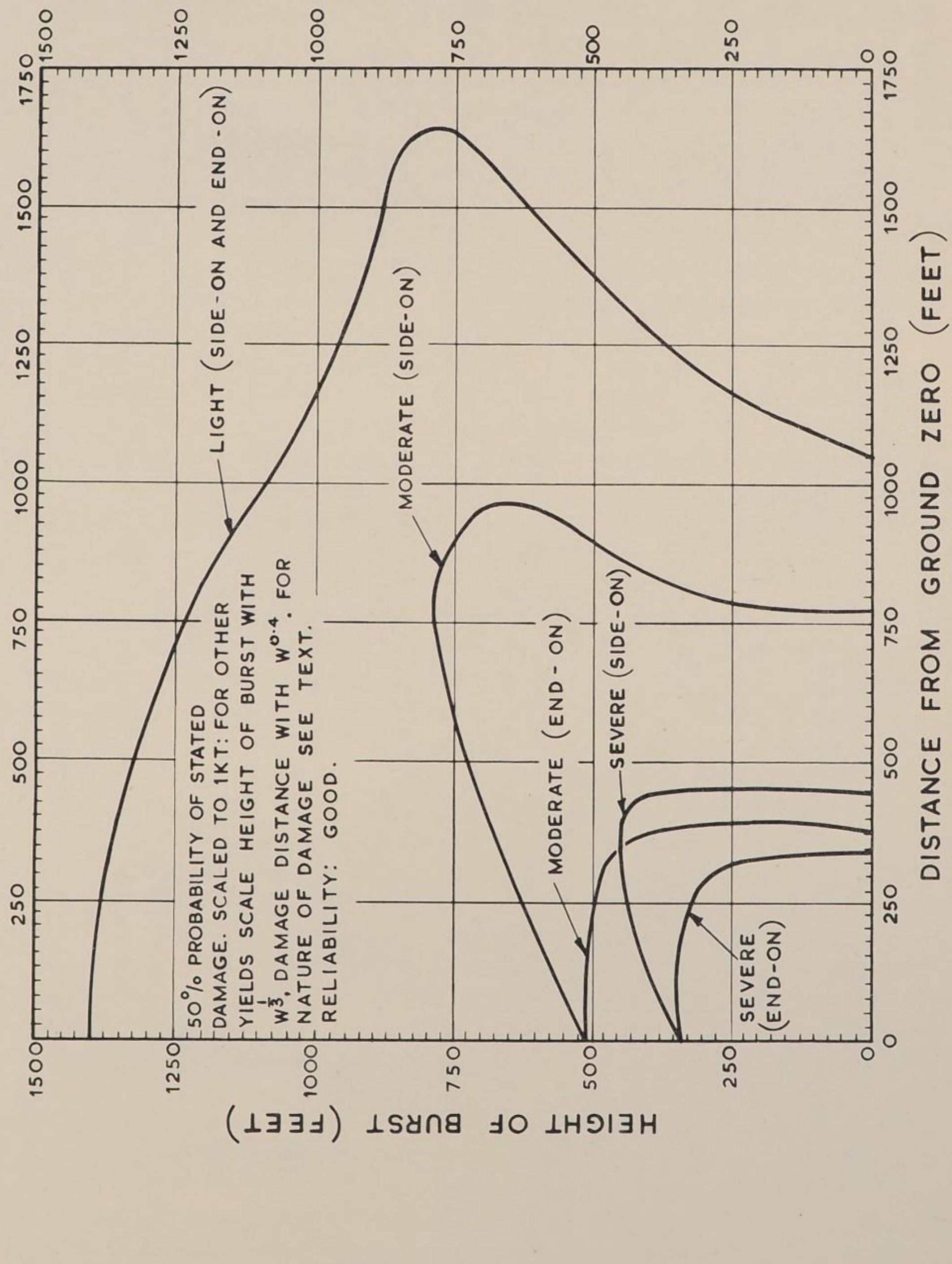
9.5.3. Motor Transport - The general remarks of Section 9.4.1. apply to motor transport and military vehicles. The curves of Figure 1 apply to all unarmoured military vehicles and also to civilian vehicles. They are also applicable to amphibian vehicles such as LVTs and DUKWs when on land. Typical examples of damage for which these curves are drawn are -

Severe - gross distortion of frame, complete disemberment possible, and great displacement;

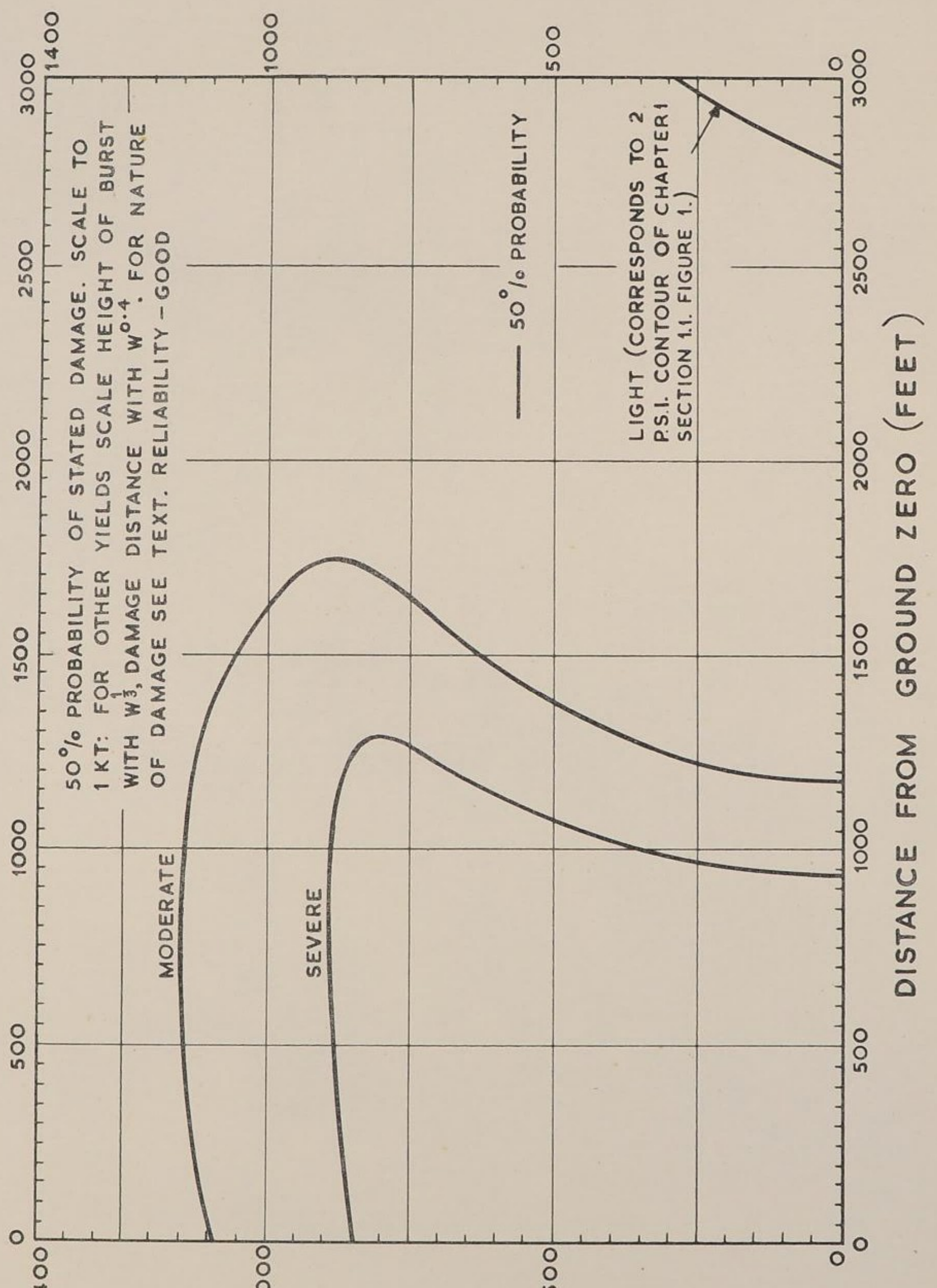
Moderate - some distortion of frame, engine mounts broken, wheels torn from vehicles, overturning probable;

Light - glass breakage, some ripping of mudguards is possible.

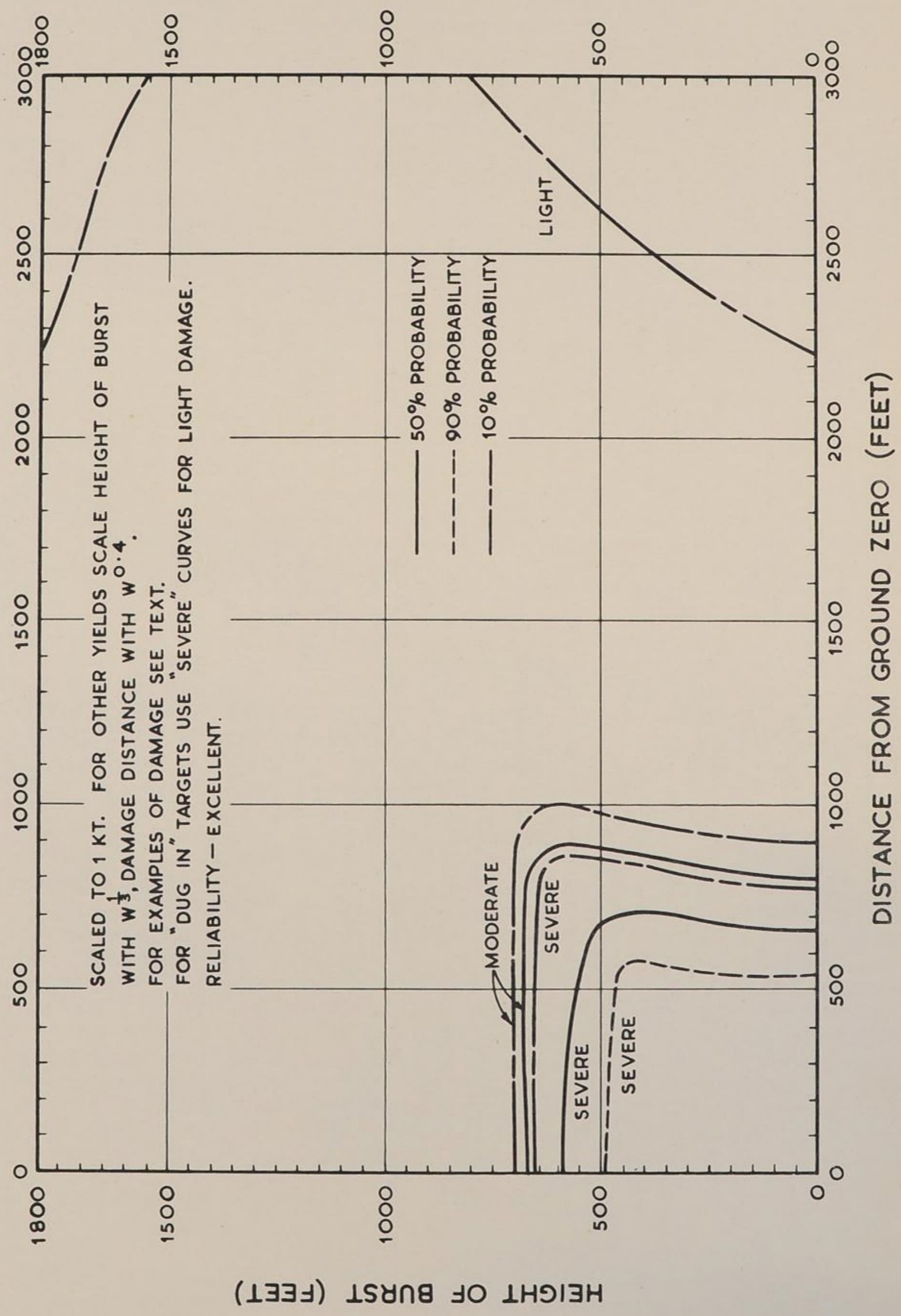
Scaling to other heights of burst follows the $W^{\frac{1}{3}}$ rule, and to other distances of damage the $W^{0.4}$ rule, as in previous sections (e.g. 9.4.4.)



DAMAGE TO LOCOMOTIVES



DAMAGE TO ROLLING STOCK



DAMAGE TO MOTOR TRANSPORT

9.6. AIRCRAFT

9.6.1. Nature of Damage to Aircraft

Aircraft components are generally constructed of rather lightweight structural elements, and because of this an aircraft is quite vulnerable to the forces imposed upon it by a blast wave. Enhanced overpressures resulting from reflection of the blast wave from the aircraft surface facing the blast may dish in skin panels and buckle stringers on that side. The blast wave overpressure, while not as large as the reflected overpressure, envelopes the aircraft and squeezes it, also dishing in panels and causing some buckling of stringers. Since the dimensions of aircraft components are usually small the diffraction process is short and does not produce any appreciable translational effect. The drag loading phase however, is relatively long and subjects an aircraft and its components to relatively large translational forces. (In aircraft loading parlance, dynamic or drag loading is usually referred to as 'gust loading'.) Since heating of the aircraft occurs more rapidly than conductive and convective cooling can take place, the thermal pulse produces stresses and may heat skin panels to such a degree that they are substantially weakened or even melted. Interior appointments and equipment, where directly exposed to thermal radiation, may ignite and cause fire damage to the aircraft structure itself.

9.6.2. Aircraft on the Ground - Air Blast Damage

The diffraction process and the drag phase have varying relative importance in producing damage to parked aircraft. In general, the diffraction process is of primary importance in the zones of light and moderate damage. In the zone of severe damage, the drag phase assumes more importance. Orientation of the aircraft has a considerable effect on damage. Revetments are expected to provide only slight blast shielding; they may, however, provide significant missile shielding. Damage to various types of parked aircraft may be estimated from the curves in Figures 1, 2 and 3. These curves are considered valid for all surface conditions. Because of the longer duration pulse from very large yield weapons, more increase in damage over that expected from small yields may result at the same blast wave overpressures. This effect is not well known quantitatively, and is not included in the damage curves. The curve in Figure 1 representing light damage to parked helicopters also estimates the range at which there is a 50% probability of grounding a hovering helicopter.

Thermal radiation - The aircraft components most easily destroyed by thermal energy are non-metallic parts such as the fabric-covered control surfaces, transparencies such as radomes and windows, de-icer boots, rubber and fabric seals, parachutes, cushions and headrests. Thermal damage to equipment of this type may be estimated from Part VI, Chapter 4, Tables 3 and 4. The primary aircraft components most vulnerable to thermal radiation are metal skin surfaces which are painted dark, since the dark paint produces a surface of high absorptivity. Proper shielding or direct modification can reduce the vulnerability to thermal radiation of both the primary and secondary components mentioned above. High performance aircraft generally have a thicker skin than lower performance aircraft, and therefore can withstand higher thermal inputs without damage. Moreover, highly polished bare metal surfaces have a reflectivity coefficient sufficiently high that damage due to thermal radiation is secondary to that caused by blast forces, except possibly, for weapons with yields in the megaton range.

Damage criteria - The isodamage curves of Figures 1, 2 and 3 apply to various types and orientations of parked aircraft. Figure 1 deals with parked helicopters, transport and liaison aircraft at random orientations. The 50% probability curves for moderate and severe damage may be used as 90% probability curves for the same degree of damage by scaling as indicated below, for a weapon of 4/10ths of the actual yield. Similarly, for conversion to 10% probability curves, scale in the same way, but using three times the actual yield. The damage definitions are as follows:-

Severe - that damage which requires at lease depot maintenance before the aircraft is fully operational.

Moderate - that damage which requires field maintenance before the aircraft is fully operational.

Light - that damage which does not prevent immediate operational use of the aircraft.

Scaling - Heights of burst and ground ranges for 50% probability of a given degree of damage may be scaled to other yields by multiplying these distances by the cube root of the yield. Resulting data may be used with good confidence in the kiloton range and with fair confidence in the megaton range. The isodamage curves in Figure 2 for randomly parked combat aircraft, and in Figure 3 for nose-on parked combat aircraft, may be adapted in a similar manner for other percentage probabilities of damage and yields of weapon. In the definition of severe and moderate damage levels'combat worthy' replaces the word 'operational' for combat aircraft.

9.6.3. - Aircraft in Flight

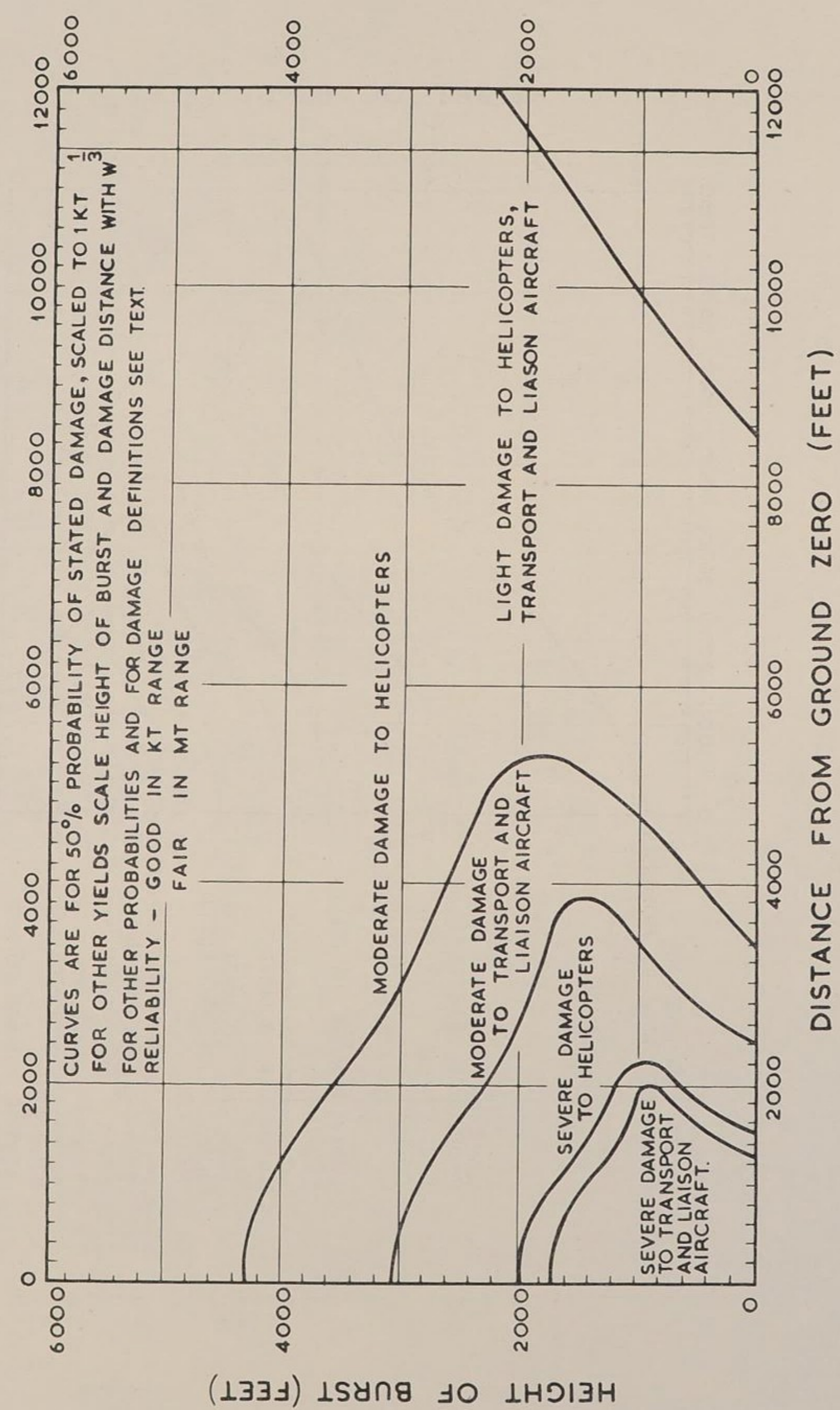
Air Blast - Since the response of airborne aircraft to blast loading is very complex, only a brief discussion is given in this manual. Where the diffraction process is the controlling factor, overpressure criteria are adequate for damage prediction. On the other hand, gust loading and the resulting response do not lend themselves to any simple criteria system of damage preduction. An airframe is a very complicated structure dynamically. Under certain conditions of gust loading, a given aircraft may fail structurally under a dynamic load of less magnitude than would cause static failure. Likewise, the same aircraft, under a different set of circumstances, may withstand a greater dynamic force than would cause failure under static loading conditions. Factors combining to influence aircraft response include true airspeed of the aircraft, the altitude of the aircraft and of the burst, the positive phase duration, the natural frequency of individual aircraft components, the weight and balance of the aircraft, the orientation and distance of the aircraft with respect to the burst, and the skill of the pilot. It must be emphasized that there is no unique scale relationship between one set of these variables and another, and that the relationship becomes even more complex for yields less than about 20 KT. Each particular problem must therefore be studied separately.

Thermal radiation - An incident thermal flux in excess of about 60 cal/cm.^{2} is considered lethal for a conventional type aircraft. For small yields the range to which 60 cal/cm.^{2} extends is usually exceeded by the lethal gust range. For aircraft with fabric control surfaces, dark painted metal surfaces of high absorptivity, or low flying aircraft capable of outrunning the destructive forces associated with the blast wave, thermal effects may exceed blast effects, even for low yields.

The degree of shielding from thermal radiation an aircraft affords its crew depends on the location of the burst relative to the aircraft, and the location of the crew within the aircraft. For a target in the air several different situations may arise, any one of which may lead to significant departures from the thermal energies predicted at a given slant range. Where the radiation traverses a path at altitudes greater than 10,000 ft. above the surface, the absorption and scattering effects decrease rapidly, with the result that observed thermal energies are greater than those calculated from the curves given in Part VI, Chapter 1. If the target is above the burst point, additional energy contributions are received by the target after reflection from the surface below. The effect is greatest with snow cover on the ground, and least over densely vegetated areas. If the target is beneath the burst the contribution of radiant energy from the ground is negligible in comparison with the energy received directly. For a burst below the target, with clouds above the target, the energy received by reflection from the cloud is negligible in comparison with the energy received directly. On the other hand, if the target is above the clouds, and the burst below, the clouds serve as a thermal shield. For a burst between the target and the cloud the situation is similar to the case of snow on the ground, since both snow and clouds are good reflectors.

Nuclear radiation - Since an aircraft is structurally light, its mass provides negligible shielding against nuclear radiation for the air crew.

Damage criteria - Figure 1 is a simplified diagram to illustrate, for several weapon yields, the general shape and order of magnitude of the volume about a typical bombardment type aircraft within which a nuclear detonation probably destroys it. This is a vertical cross section of the lethal gust envelope in the plane of symmetry through the longitudinal axis of the aircraft. Curves are given for yields between $\frac{1}{2}$ and 20 KT. For yields greater than 20 KT, the lethal radius from a burst in the aircraft plane of symmetry may be obtained by scaling the 20 KT envelope with $W^{\frac{1}{3}}$. Note that these curves are presented primarily to illustrate general shapes and magnitudes of lethal gust envelopes for bombardment type aircraft. It is NOT intended that numerical data derived be applied directly to any specific aircraft models. (Editor's Note. -It is believed that the original curves were derived for B.29 type of aircraft structures).



DAMAGE TO AIRCRAFT ON THE GROUND.
COMMUNICATIONS & TRANSPORT TYPES, RANDOM ORIENTATION

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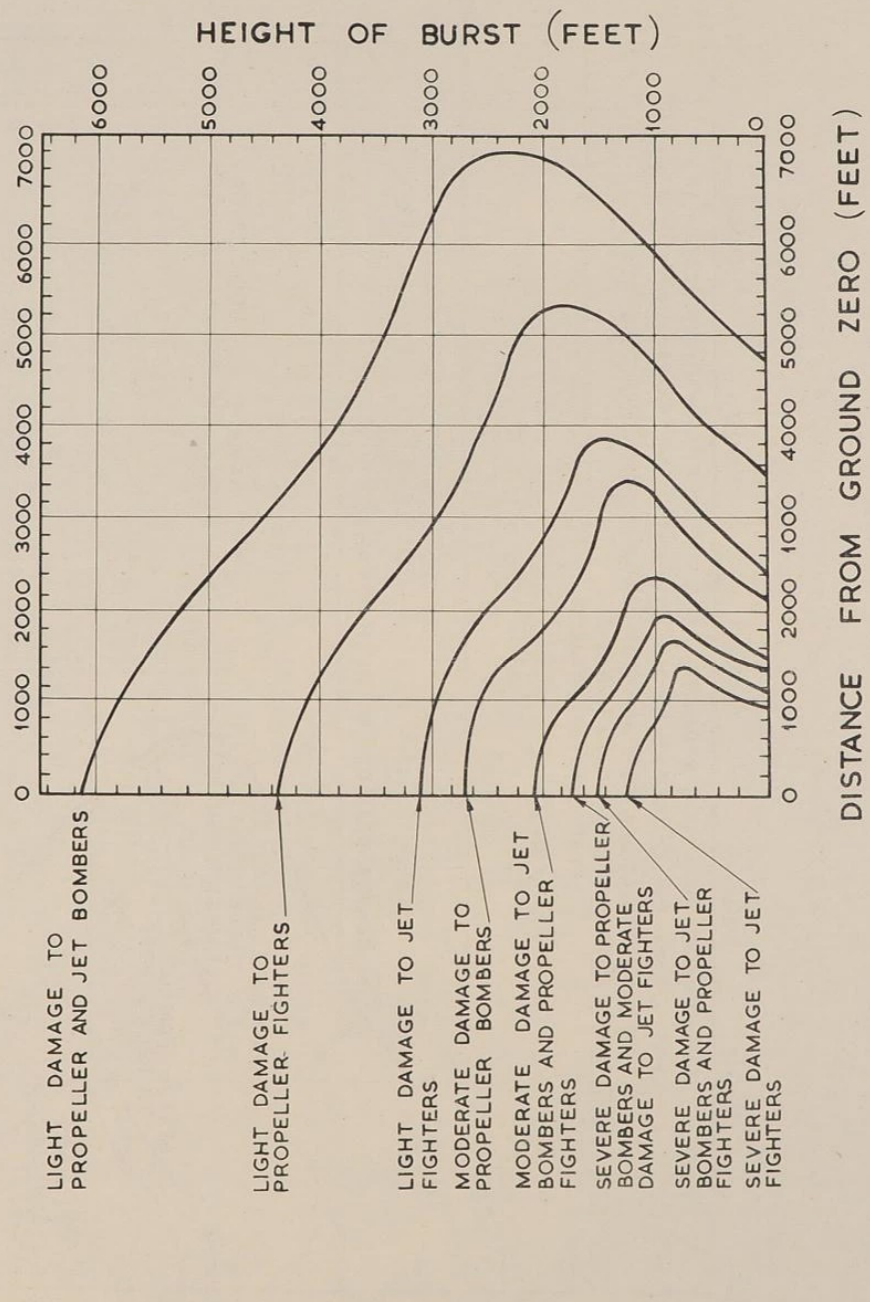
PART III
CHAPTER 9.
SECTION 9.6.2.
FIGURE 2.



DAMAGE TO AIRCRAFT ON THE GROUND.
COMBAT TYPES, RANDOM ORIENTATION

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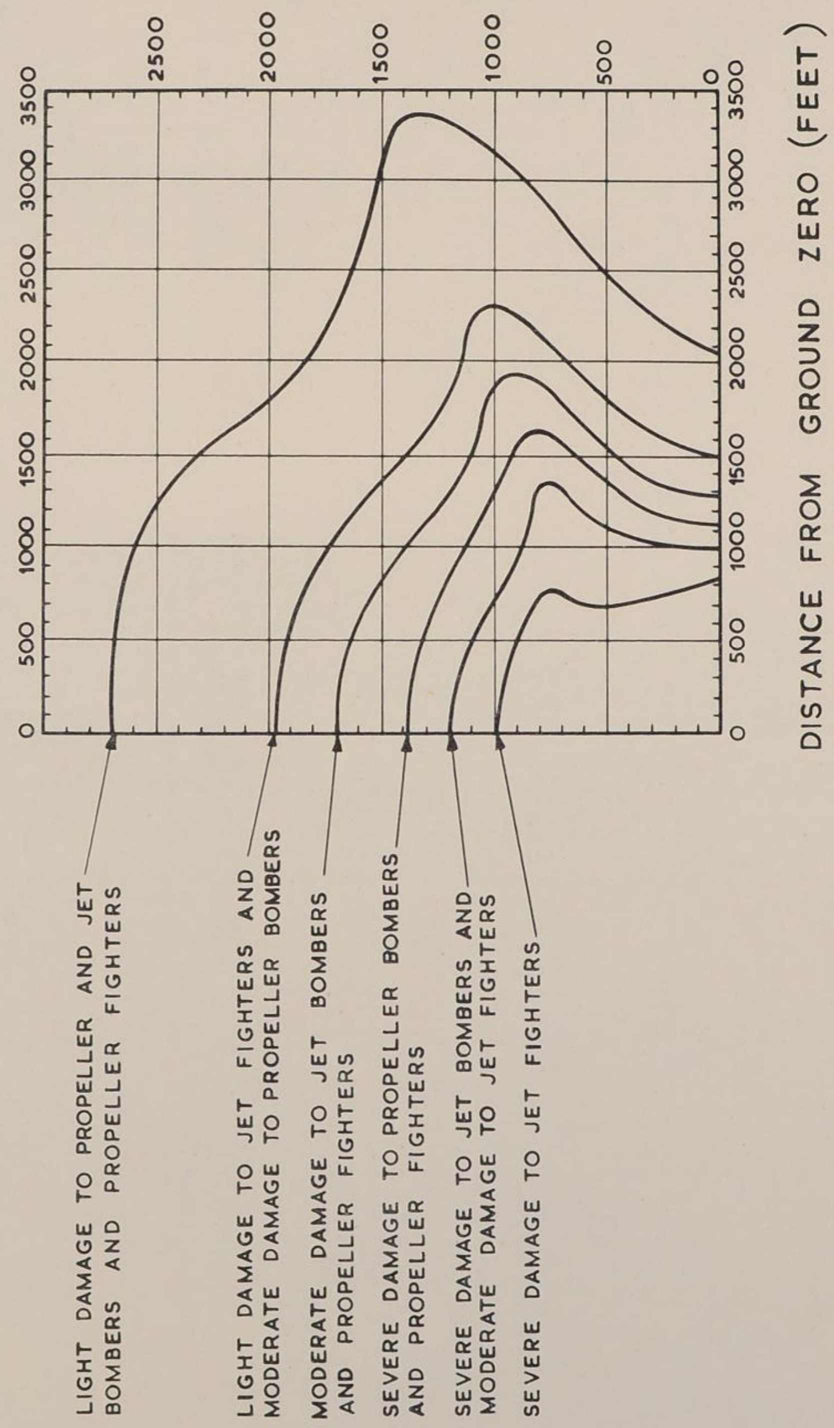
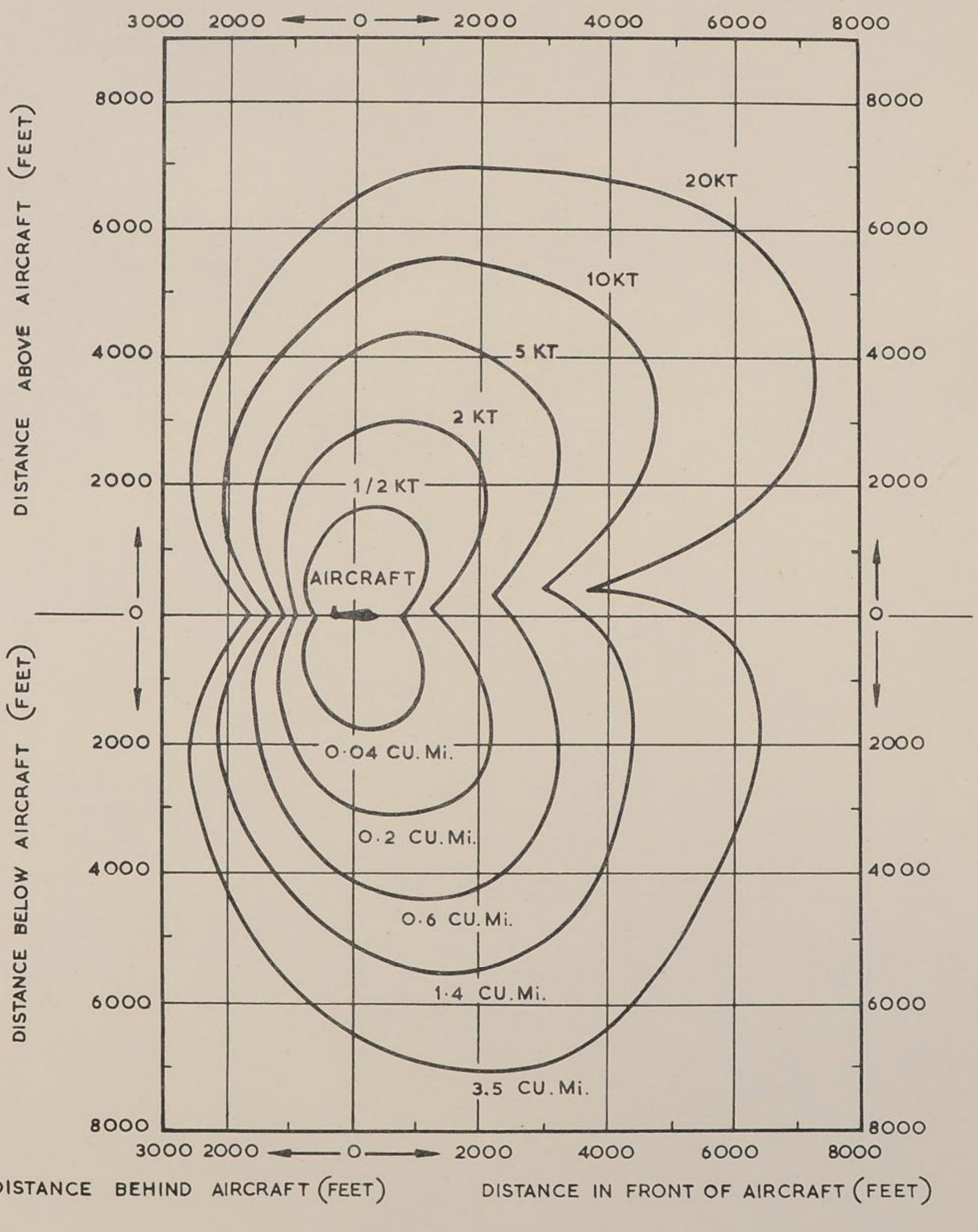


DAMAGE TO AIRCRAFT ON THE GROUND.
COMBAT TYPES, NOSE-ON ORIENTATION

THESE CURVES ARE PRESENTED PRIMARILY TO ILLUSTRATE GENERAL SHAPES AND MAGNITUDES OF LETHAL GUST ENVELOPES FOR BOMBER TYPE AIRCRAFT. IT IS NOT INTENDED THAT NUMERICAL DATA DERIVED BE APPLIED DIRECTLY TO ANY SPECIFIC AIRCRAFT MODELS. CUBE ROOT SCALING OF THE 20 KT CURVE WILL INDICATE APPROXIMATE ENVELOPES FOR LARGER YIELDS.



DAMAGE TO AIRCRAFT IN FLIGHT.
TYPICAL LETHAL GUST ENVELOPES

9.7. SHIPS AND MARITIME OBJECTS

9.7.1. Surface Vessels *

In addition to damage by water shock and surface waves, as described in Part V, mechanical damage to surface ships may be caused by air blast. Thermal damage to shipping is not considered an important factor in that it does not, of itself, cause sinking or immobilisation. As the depth of a burst is decreased, a transition from water shock to air blast as the controlling damage parameter occurs. Air blast is also the controlling damage parameter in the case of air bursts. Peak pressure is considered a satisfactory parameter for estimating damage to ships from air blast. A peak overpressure of 5 p.s.i. causes light damage to most types of surface ships. The peak overpressures required for severe damage vary from 25 p.s.i. for destroyers, to 45 p.s.i. for battleships; Figures 1 and 2 give damage ranges for a 1 KT burst. For heights of burst less than 600 ft., and depths of burst less than 800 ft., heights and distances scale with $W^{\frac{1}{3}}$ for other yields, although owing to the limited amount of data available only fair reliability can be assumed. The predictions also become less reliable at the shallower depths of burst. A tabulation of peak overpressure required to cause ship damage is given in Table I for use with burst heights greater than those shown in Figures 1 and 2. For these burst heights distances to which these overpressures extend are obtained from the usual height of burst/overpressure curves.

TABLE I - Surface Ship Peak Air Overpressure Damage Criteria

	Peak Air Overpressure (p.s.i.)		
	Severe	Moderate	Light
Aircraft Carriers	30	20	5
Battleships	45	25	5
Cruisers (heavy)	40	20	5
Cruisers (light) (AA)	30	20	5
Destroyers	25	15	5
Pontoons (for pier construction)	60	-	-
Transports	30	20	5
LSTs & Landing Craft and Landing Vehicles	25	15	5
Submarines (surfaced)	80	60	-

The damage levels are defined as follows:-

Severe - (Probable sinking). The ship is sunk or is damaged to the extent of requiring rebuilding.

Moderate - (Immobilisation) The ship requires extensive repairs. This includes damage to certain shock-sensitive components or to their foundations, such as propulsion machinery, boilers, and damage to interior equipment.

Light This category includes damage to electronic, electrical and mechanical equipment; however, the ship may still be able to operate effectively.

* Note: this information is of American origin, whereas British estimates (L.C.A.F.O.117/55) indicate somewhat greater damage radii corresponding to less severe pressure criteria.

9.7.2. Submarines

Data for surfaced submarines are given in Table I above; data for submerged submarines are given in Part V.

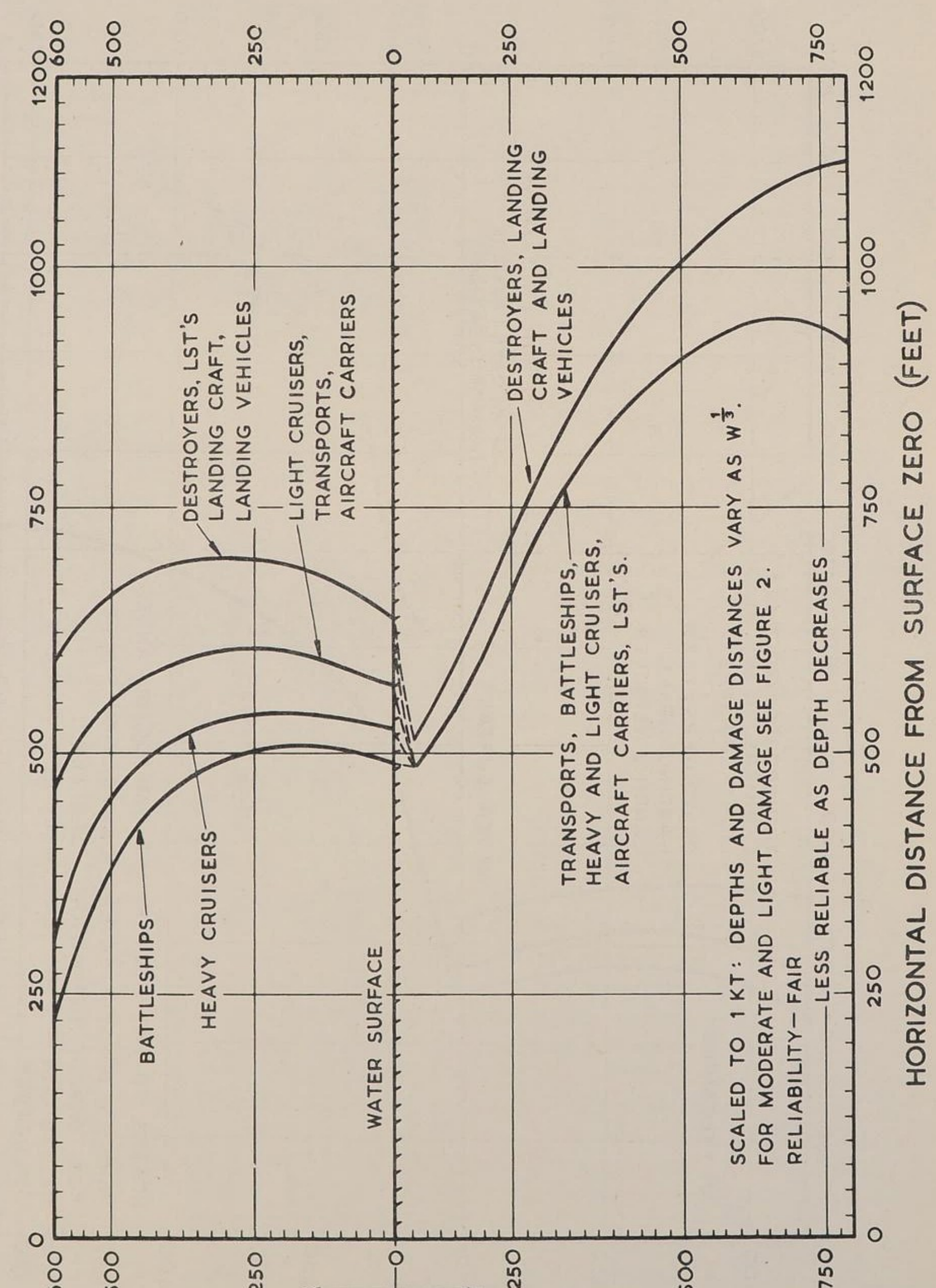
9.7.3. Dams, Lock Gates and Harbour Installations

Dams - A concrete gravity dam with the reservoir water level higher than about half dam height, is most vulnerable to an underwater burst, and damage under such conditions is therefore dealt with in Part V. A concrete gravity dam with the water reservoir level less than about half dam height is most vulnerable to a surface burst upstream from the dam. An air burst on the down stream side of the dam is the least effective method of breaching concrete gravity dams. Air blast from such a burst or from a burst on top of the dam is a primary damaging agent against powerhouse structures, and this should be analysed according to structural type as in Section 9.2. The damaging situations for lock gates and caissons are similar to those for gravity dams.

Harbour Installations - Air blast is the most important damage mechanism for most structures around a harbour. Air blast damage to surface structures is given in Section 9.2. For canal or river locks, where the water level around the gates is low, air blast is effective in making the locks inoperable by damage to the gates. Damage by cratering is dealt with in Part IV, and damage by water waves in Part V. Thermal radiation is no hazard to dams, but may start large fires by ignition of kindling material in dockside areas.

Note. Floating Bridges

Data on floating bridges are given in Section 9.2.8. above.



SEVERE DAMAGE TO SURFACE SHIPS
(PROBABLE SINKING)

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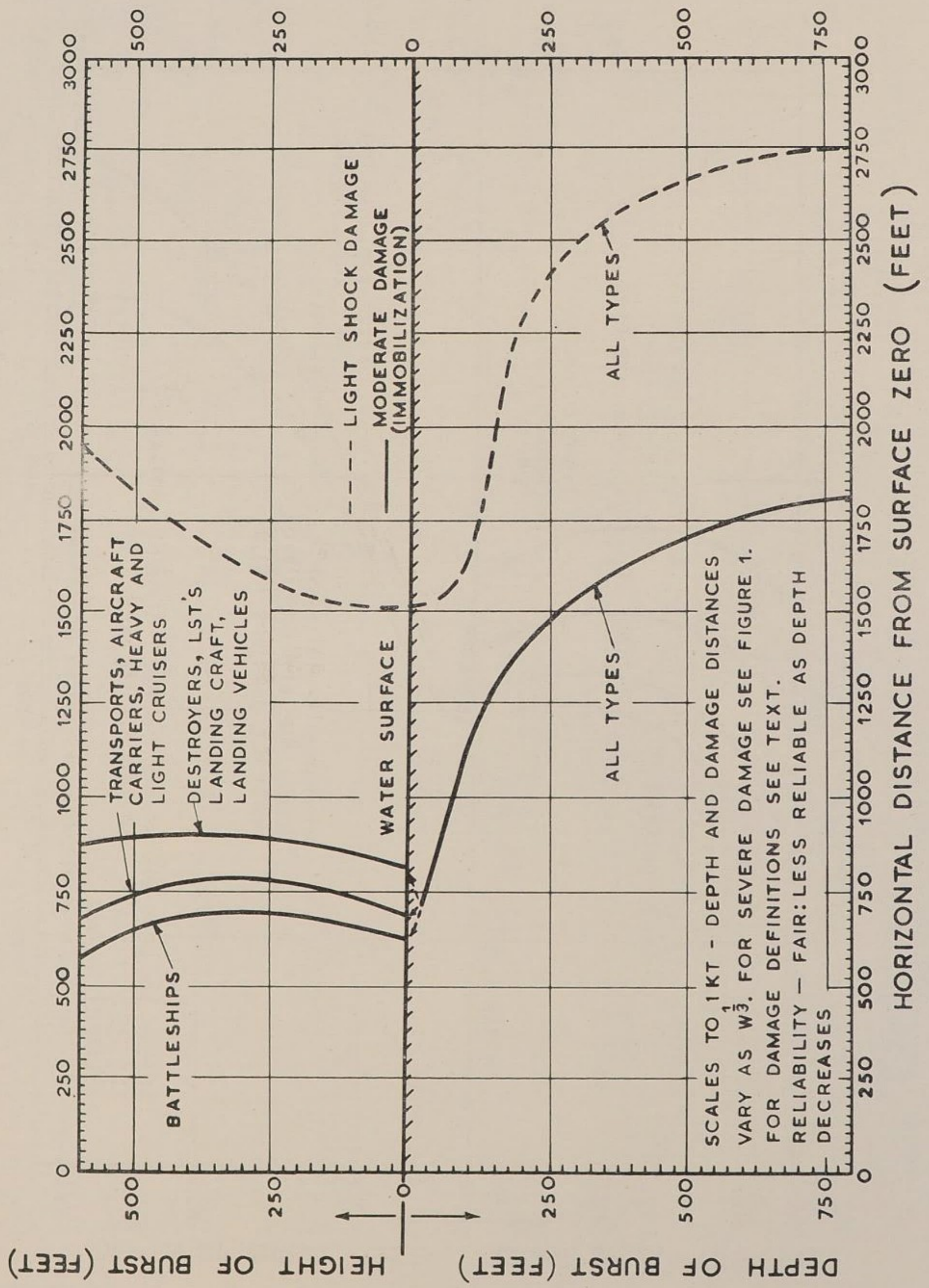

MODERATE AND LIGHT DAMAGE TO SURFACE SHIPS

SECRET ATOMIC

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9.8 PERSONNEL

9.8.1. Injury by Blast Overpressure

The air blast from a nuclear detonation may cause casualties among human beings in two ways -

(a) Large pressure differences resulting from the blast wave overpressures may cause direct damage to lungs, abdominal organs, and other fluid or air-filled body organs. Translational forces on the human body may throw it for considerable distances.

(b) Personnel may become casualties through being injured or killed by the collapse of structures, by overturning and displacement of vehicles and equipment, or by missiles resulting from the air blast effects of the explosion.

The human body is relatively resistant to the crushing forces which result from air blast loading. Based on data obtained from high explosive detonations, it is estimated that of the order of several hundred p.s.i. peak overpressure is required to cause death in humans, provided no translational motion occurs. Severe injury may result at much lower pressures. Ear drum rupture may result at peak overpressures of 7 to 15 p.s.i., some cases have been known at 2-4 p.s.i. Ref(1). Early evacuation of all such cases will generally not be required, therefore the overall effectiveness of a military unit will not be hampered by the occurrence of these injuries. Both ear drum rupture and other bodily damage from this type of loading are largely dependent upon the characteristics of the shock front. If the rise time of the blast wave is long, the body organs are subjected to less severe pressure differences. Also, the body is able to adapt itself better to high overpressures when the pressure build-up time is long. Consequently, the probability of injury is reduced. Although little is known about the crushing effect of a long duration blast on the human body, increasing the duration probably lowers the peak pressure required for a given effect. Blast may be a major problem where the design of the structure permits build-up of the blast pressures through multiple reflections. Such a situation may be found in shelters, permanent type gun emplacements, or under similar circumstances where thermal and nuclear radiation are shielded out.

References

(1) Medical effects of Atomic Bombs in Japan.
Oughterson and Warren. U.S.Government Printing Office 1956.

9.8.2. Injuries Caused by Translational Motion

Bodily displacement of an individual exposed to a blast wave depends primarily on drag forces. Since the human body is relatively small, and the blast wave almost immediately envelopes it, the diffraction process is short. Displacement may be predicted with reasonable accuracy if the burst position, yield, and the orientation of the human body are known. The positive phase duration of the blast wave increases with increasing yield, and as a consequence the load causing translation is applied over a longer period of time. The translational force applied depends also on the exposed frontal surface area of the human body. An individual standing in the open is subjected to much larger forces than an individual lying on the ground surface. Adopting a prone position at the instant of an atomic bomb flash is effective in reducing the liklihood of injury from bodily displacement. Time of

arrival of the shock at a given overpressure increases with increasing yield and may be estimated from the data given in M.E.A.W. Chapter I, Data Sheet 1.8. The translational forces are reduced for an individual who is behind a building or in a shelter which is sufficiently resistant to withstand the blast forces. Foxholes afford almost complete protection against bodily displacement.

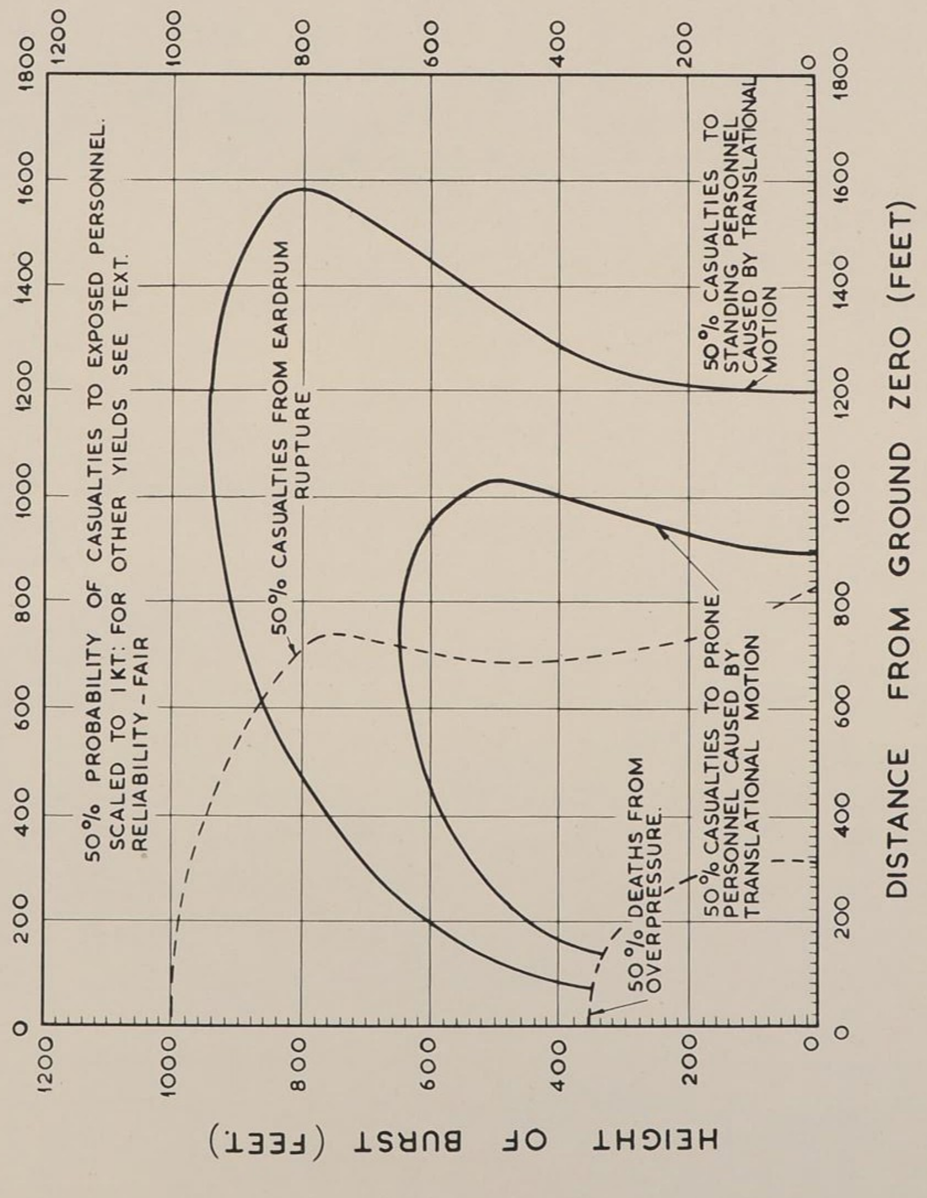
Criteria for Injury - Although no direct correlation is known between displacement and injury, it is reasonable to assume that some such relationship exists. The production of casualties from displacement depends almost completely on the nature of the impact. Some individuals may survive large displacement, whereas severe injury or death may occur with relatively small displacement. Severity of injury depends on the nature of the object or objects with which the displaced body collides and the nature of the impact, whether glancing or solid. Because increased yield results in increased positive phase duration and displacement, the probability of impact occurrences increases. The probability of impact occurrences likewise depends on the nature of the terrain and surface configuration. If solid impact occurs, it is estimated that body velocities of about 12 ft. per second produce serious injury approximately 50% of the time while collision at about 17 ft. per second results in about a 50% mortality. Figure 1 is a plot of height of burst against ground range at which 50% of standing and of prone personnel in the open are expected to become direct blast casualties. The curves are drawn for 1 KT, and may be scaled to other yields by multiplying the burst heights by the cube root of the yield and the ground distances by the 4/10th power of the yield in the case of the dashed curves. In the case of the full line curves both height and distance vary as the cube root of the weapon yield.

On account of the many possible variables the reliability of these curves can only be considered as fair.

Note. Some theoretical estimates for high yield weapons will be found in Reference (1)

References

(1) Estimate of some blast wind effects of Megaton bombs. A.W.R.E. Report No. E6/55
(Secret/Atomic/Discreet/Cleared for Canada).



DIRECT BLAST CASUALTIES TO PERSONNEL

9.8.3. Indirect Blast Injury: Casualty Estimates

Most blast casualties in cities are caused by damage to buildings. The occupants may be crushed, trapped, or struck by building materials projected by the blast. The number of casualties caused by a nuclear weapon will, of course, be dependent on the degree of protection afforded by the buildings and upon the extent to which advantage has been taken of such protection. For these reasons estimates of casualties cannot be expected to be more than rough guides to be used for Civil Defence planning.

Casualty figures from Hiroshima and Nagaski cannot be directly applied to Western conditions because of differences in house construction, and because the populations of these cities were not aware of the dangers to which they were exposed. But a method has been devised (1) in which the estimates of damage to British houses, (given by the British Mission to Japan), are used in conjunction with H.E. data from the last war on casualty rates in damaged houses to provide casualty rates for nuclear weapons.

The H.E. material was, of course, based on the high standard of rescue possible in the last war, and it has been necessary to adjust the casualty rates, since organised rescue of trapped occupants from the more severely damaged buildings will hardly be possible in nuclear war. The adjusted rates are given in Table I below, and can be used to derive casualty estimates.

TABLE I. CASUALTY RATES FOR OCCUPANTS OF BRITISH HOUSES

DAMAGE CATEGORY	KILLED	SERIOUSLY INJURED	LIGHTLY INJURED
A ($>$ 15 p.s.i.)	80%	5%	1%
B (15-$7\frac{1}{2}$ p.s.i.)	40%	7%	5%
Cb($7\frac{1}{2}$-3 p.s.i.)	-	9%	6%
Ca(3-$1\frac{3}{4}$ p.s.i.)	-	2%	2%
D ($1\frac{3}{4}$-1 p.s.i.)	-	-	-

Note: (1) these casualty rates are related to blast effects only.
(2) typical 2-storey British houses assumed, with 9" or 11" brick walls.
(3) assumed that whole population is in such houses, taking best advantage of protection afforded.
(4) for definitions of damage categories see Section 9.1.3.

The pressure ranges for the various categories of damage given in Table I may be used in conjunction with the appropriate blast pressure curves to derive the extent of damage for any power of nuclear weapon.

American analysis of somewhat limited Japanese data for reinforced concrete structures suggests that on account of their much greater blast resistance, collapse is associated with almost 100% fatality. Moderate damage may be associated with 10% dead, 15% seriously and 20% lightly injured and light damage with 5%, 5% and 15% respectively. The corresponding damage distances are given in Section 9.2.2. Figure 2, and

Section 9.2.6, Figure 2. To make a good estimate of casualty production in other structures it is necessary to consider the type of structural damage that occurs and the characteristics of the resultant missiles. Glass breakage extends to considerably greater ranges than almost any other structural damage, and may be expected to produce large numbers of casualties at ranges where personnel are relatively safe from other effects, particularly for an unwarned population.

American estimates are that in cases of severe damage some 60% of the survivors may have to be extricated by rescue squads. Without rescue they may become fire or asphyxiation casualties, or in some cases be subjected to lethal doses of residual radiation.

A major cause of personnel casualties in exposed situations is flying missiles. These missiles have low velocities and many crushing injuries may be expected, in contrast to penetrating wounds caused by high velocity missiles. The missile density and characteristics are largely a function of the target. Where the target area is relatively clean and there is little material present subject to fragmentation and displacement, fewer injuries from missiles are expected in the open than from debris within structures at comparable distances. When the target complex presents many possible sources of missiles, this cannot be the case. Personnel in a prone position are less likely to be struck by flying missiles than those who remain standing. Those who succeed in getting into bunkers, foxholes, or in defilade, probably achieve almost complete protection from the flying missile hazard.

Personnel in vehicles may be injured as the result of the response of the vehicle to the blast forces. Padding where applicable, and the use of safety belts, helmets and harnesses virtually eliminates this source of casualties, at least within armoured vehicles. In the absence of these protective devices, serious lacerations may result from impact with sharp projections within the vehicle interior, but these vary greatly among different vehicles and at different positions within the same vehicle. Comparative numbers of casualties are almost impossible to assess in this respect, due to the many variables which are involved in the problem.

References

(1) Civil Defence Joint Planning Staff Paper C.D.J.P.S.(E.A.)(48)14 (Revised).

(2) Manual on the Effects of Atomic Weapons. A.W.R.E. (Secret/Atomic)

(3) Capabilities of Atomic Weapons A.F.S.W.P. (Secret/Atomic)

9.9. VEGETATION

9.9.1. Introduction

Although forests or tree stands may afford troops deployed in them significant protection against certain effects of atomic bomb detonation (e.g. thermal radiation), the forests themselves are quite vulnerable to some of these effects. Falling limbs and trees create a missile hazard, and the resultant debris on the forest floor may impede the movement of troops and most vehicles. In dry, windy weather, forest fires may be initiated by an atomic bomb detonation, with smoke and flame extending the range of hazardous effects from the bomb itself many times. Forest vulnerability depends on recent local weather history and upon the type of tree stand involved. Forest kindling fuels and types of stand are discussed in the paragraphs which follow from the blast damage point of view only. Thermal aspects of the problem are dealt with in Part VI.

9.9.2. Types of Forest Stand

For convenience in discussion of blast effects, forest stands are divided into three types.

Type I Stand - Improved natural or planted conifer forests of European Type.

These forests characteristically grow in regular blocks usually with definite borders. Tree spacing is uniform, with only small patches of ground visible through the canopy from above. Trees are of uniform height and nearly the same diameter. Viewed from above, the crown canopy appears smooth. Within the stand there usually are found low stumps resulting from thinning, clear lower stems as a result of pruning, and little or no underbrush, combining to give the interior of the stand a clear appearance and affording good visibility and easy passage into the forest.

Type II Stand - Naturally Occurring Unimproved Conifer Forests that developed under Unfavourable Growing Conditions -

Unfavourable growing conditions result from shallow rocky soil, deficiant annual rainfall, short growing season with unfavourable temperatures (i.e. higher altitudes or higher elevations), and unfavourable temperatures (i.e. higher altitudes or higher elevations), and unfavourable topography such as poorly drained flats or steep slopes. Random tree spacing is a characteristic, with all tree sizes represented. The crown canopy generally has an uneven appearance. Large stands often contain bare areas with irregular borders.

Type III Stand - All Broad Leaf Forests, and Naturally Occurring Unimproved Conifer Forests, that have developed under Favourable Growing Conditions -

Favourable growing conditions are associated with deep, generally rock-free soil; adequate annual rainfall; long growing season with favourable temperatures (i.e. middle latitudes and lower elevations); and favourable topography such as well-drained flats and moderate slopes, or along stream courses. Random tree-spacing is characteristic, with all tree sizes represented. The crown canopy is generally uneven in outline. Large stands often contain bare areas with irregular borders. Tree crowns and vegetation in general are vigorous in appearance.

9.9.3 Damage Criteria - Height of burst/damage distance curves for severe and light damage by air blast are presented in Figures 1, 2 and 3. The tree stand types referred to are those given above. Severe and light damage are defined in terms of length of stems down per acre, approximately 1500 ft. per acre for light damage and 9,000 ft. per acre for severe damage. These criteria are shown in terms of percentage of trees broken in Table I. The approximate number of trees per acre that may be expected for the three types of forest stand is also shown.

TABLE I - Percentage of Trees Broken for Light and Severe Damage to Forest Stands

Stand type	Trees per Acre	Light damage percent of trees broken	Severe damage percent of trees broken
I	75	15	90
II	260	10	60
III	200	10	60

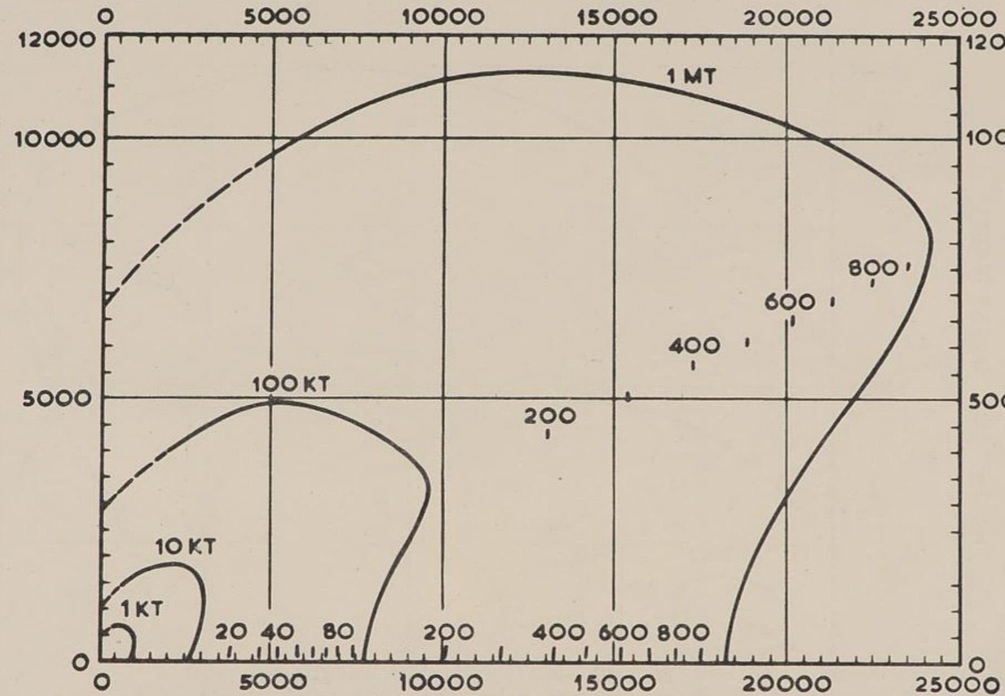


FIG. A

SCALE 1 MT CURVE WITH $W^{\frac{1}{3}}$ FOR LARGER YIELDS.
FOR DAMAGE DEFINITIONS SEE TEXT.
RELIABILTY – GOOD.

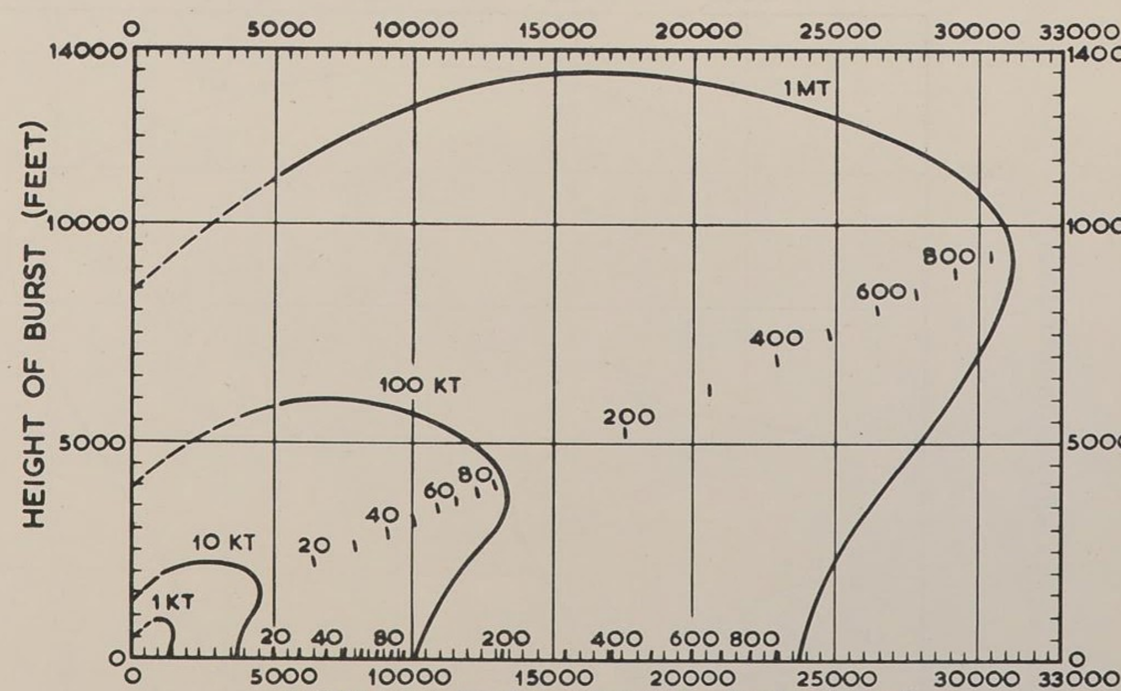


FIG. B

FIG. A. SEVERE DAMAGE TO TYPE I FORESTS
FIG. B. LIGHT DAMAGE TO TYPE I FORESTS

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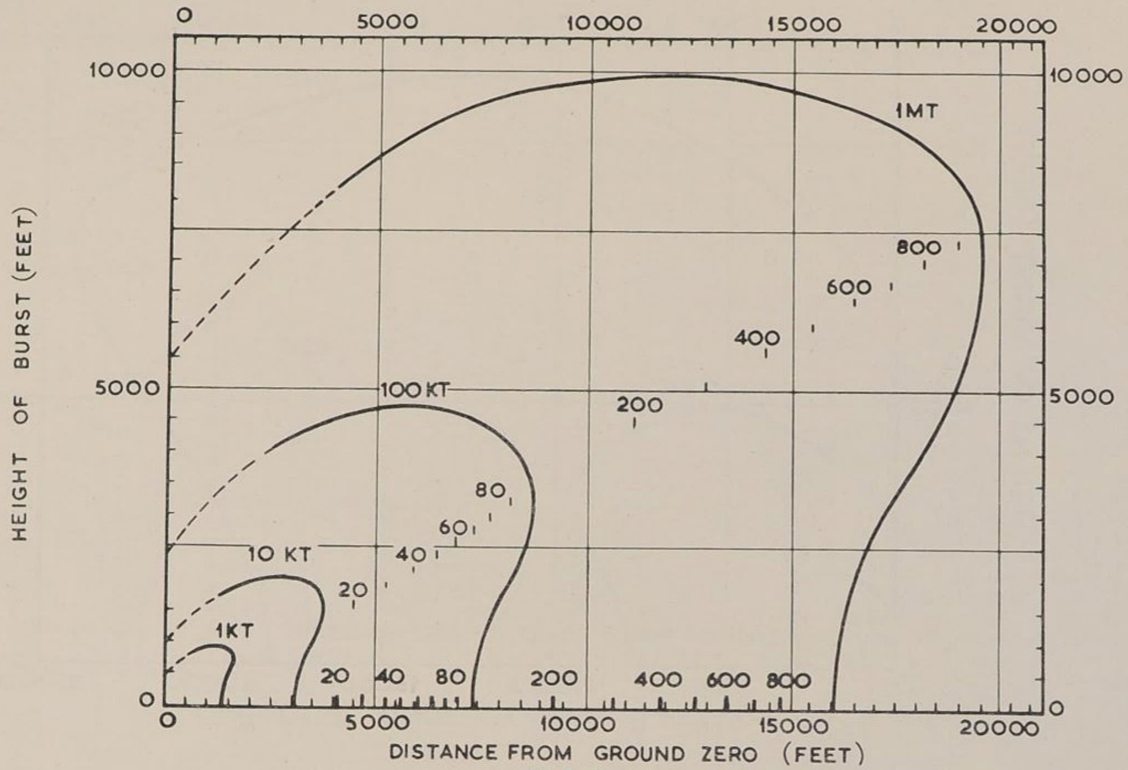

FIG. A

SCALE 1MT CURVE WITH $W^{1/3}$ FOR LARGER YIELDS. FOR DAMAGE DEFINITIONS SEE TEXT. RELIABILITY – GOOD.

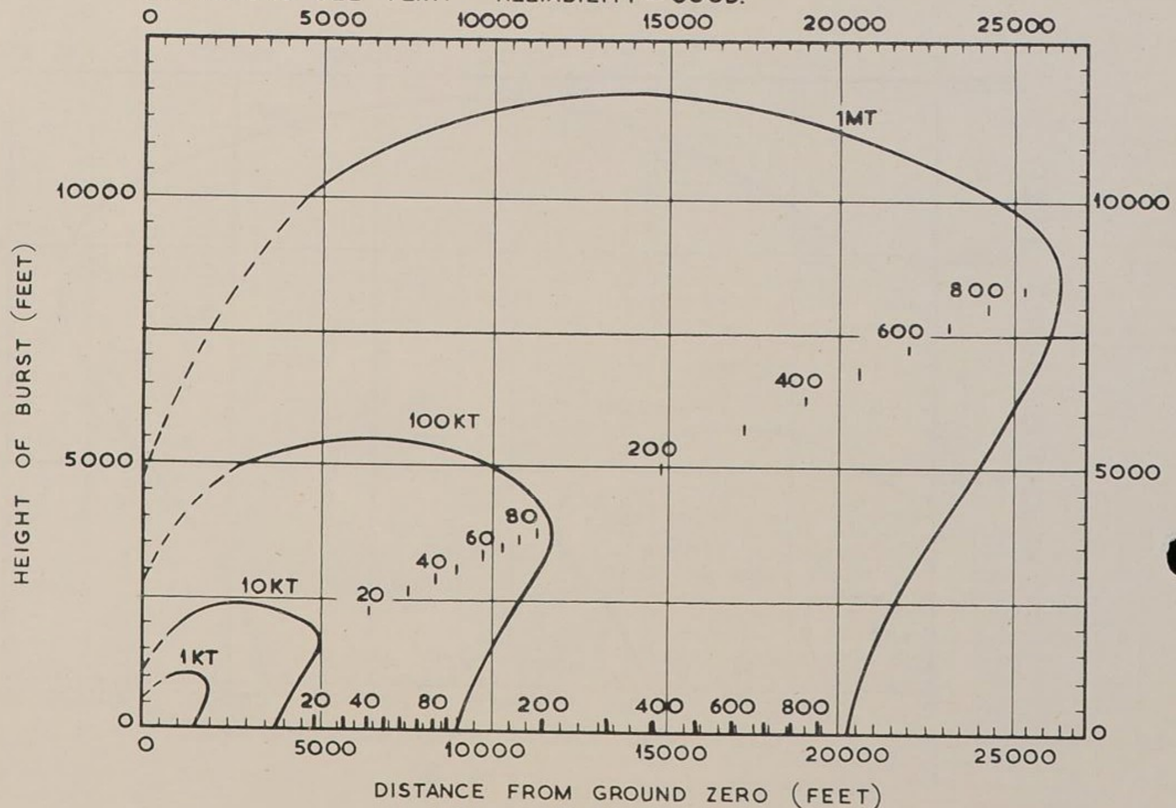

FIG-B

FIG. A. SEVERE DAMAGE TO TYPE II FORESTS
FIG. B. LIGHT DAMAGE TO TYPE II FORESTS

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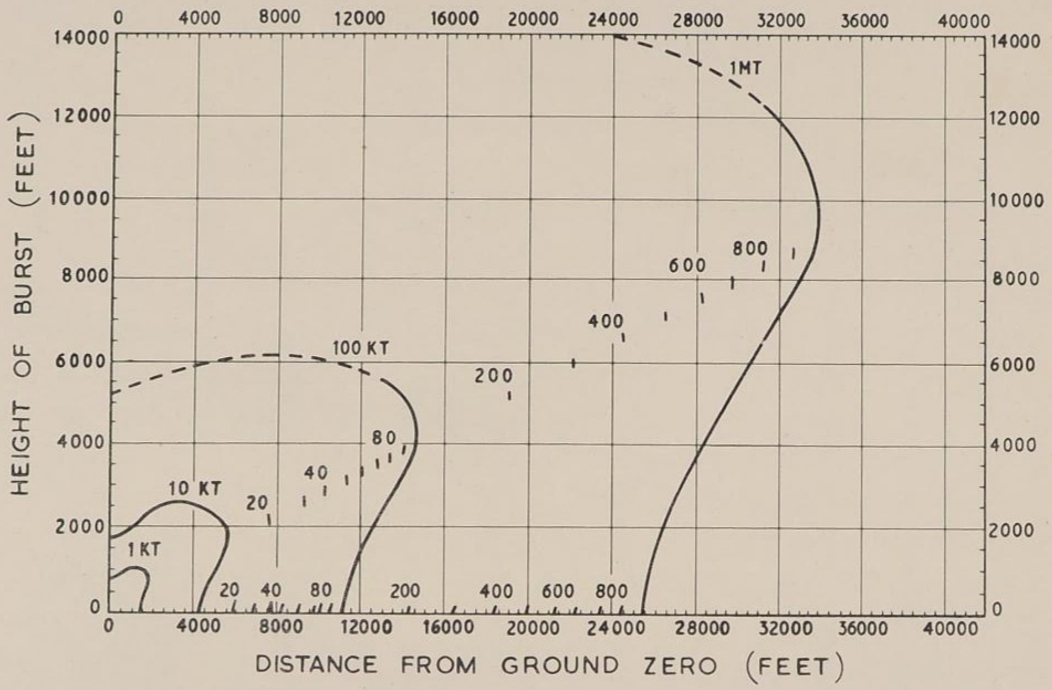

FIG. A

SCALE 1 MT CURVE WITH $W^{\frac{1}{3}}$ FOR LARGER YIELDS. FOR DAMAGE DEFINITIONS SEE TEXT. RELIABILITY — GOOD

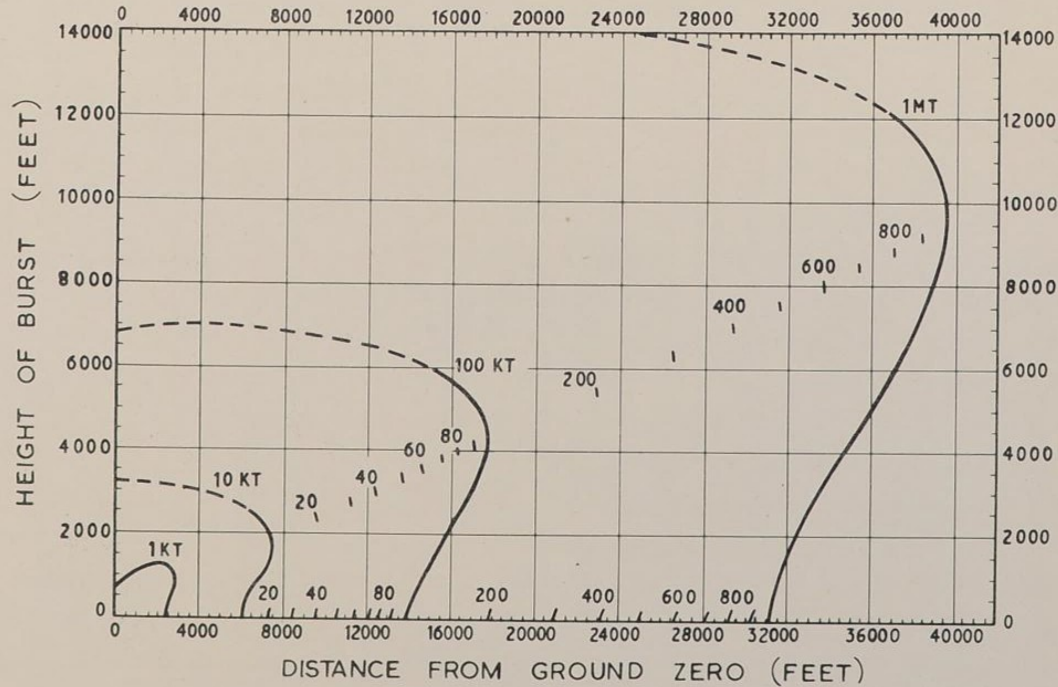

FIG. B

FIG. A. SEVERE DAMAGE TO TYPE III FORESTS
FIG. B. LIGHT DAMAGE TO TYPE III FORESTS

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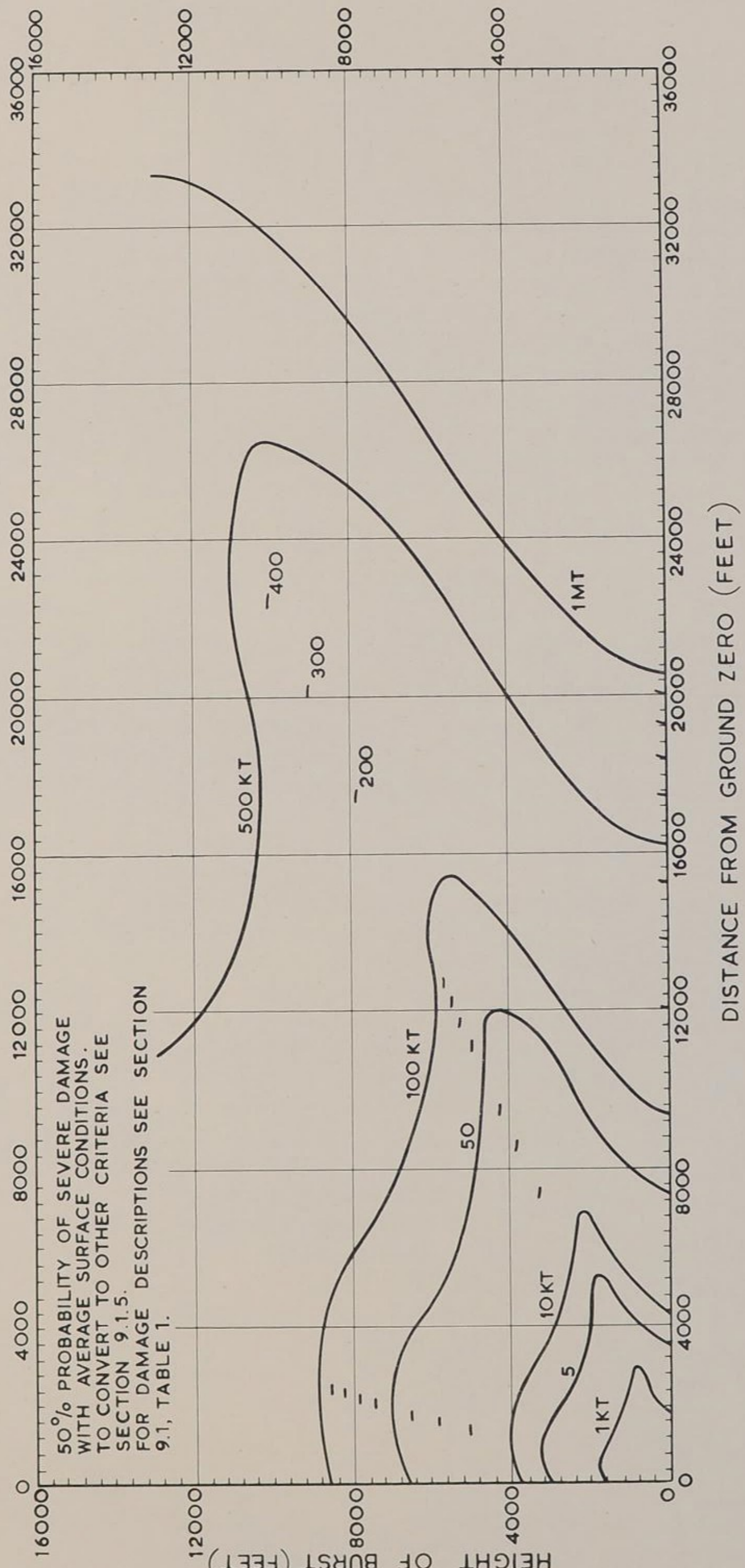


DAMAGE TO SINGLE AND 2-STOREY
WOODEN FRAME HOUSE

9.2.8. Bridges. Damage to bridges by bursts at low heights (up to $400W^{\frac{1}{3}}$ft.) is shown in Figure 1 for yields from 0.1 KT to 100 MT. The curves apply to highway and railway truss bridges for orientations of blast propagation from 45° to 90° from the longitudinal bridge axis. The given distances of Figures 2 and 3 are to be reduced to 60% for an orientation of 0° for all span lengths. In the case of orientations between 0° and 45° a linear interpolation is to be used.

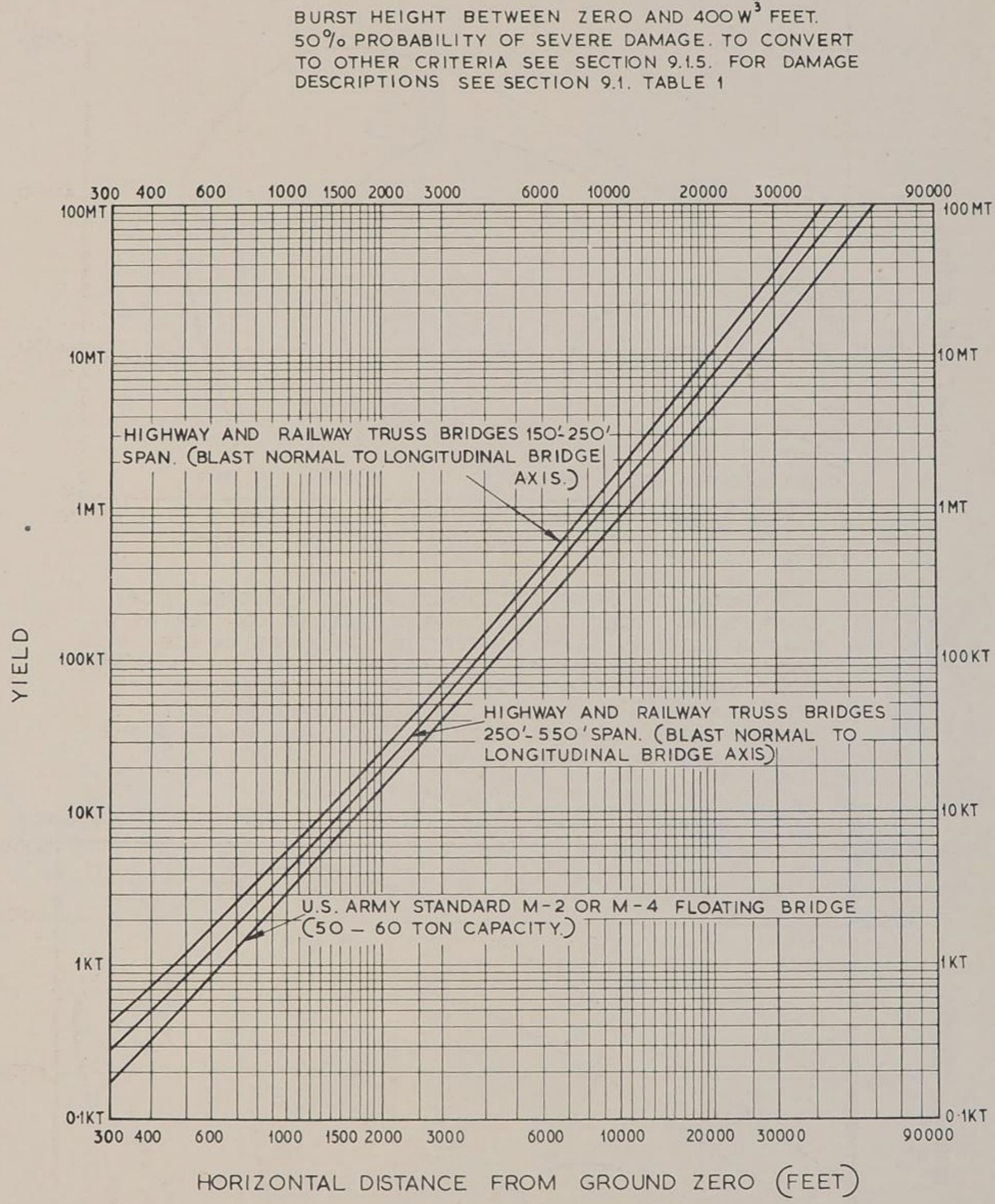
The damage curves of Figure 4 apply to floating bridges types M-2 or M-4 at all orientations.≠ Typical examples of severe, moderate and light damage are given in Table I of Section 9.1.4. The adaptation of these curves to give other damage levels or probabilities of damage is described in Section 9.1.5. The allowances to be made in the case of airblast damage from underground bursts are given in Section 9.1.6.

≠ Note. Details of the U.S. Army standard floating bridges M-2 and M-4

M-2 - Capacity 44 tons safe, 50 tons risk, corresponds roughly to Class 40 safe and Class 50 for risk respectively. Two steel treadway tracks $45\frac{1}{2}$ in. wide with 63 in. gap. Rubber pneumatic floats of 24 tons total buoyancy at a centre spacing of 12 ft.

M-4 - Capacity roughly Class 50. Full width roadway of longitudinal aluminium baulks, carried on light alloy or steel open pontoons.

9.2.9. Oil Storage Tanks - The oil storage tanks for which damage curves are given in Figure 1 were 30 ft. high and 50 ft. in diameter. Empty tanks would be considerably more vulnerable and would probably suffer severe damage at ranges where only moderate or light damage would result when full. Typical examples of severe, moderate and light damage are given in Table I of Section 9.1.4. The adaptation of these curves to give other damage levels or probabilities of damage is described in Section 9.1.5. The allowances to be made in the case of airblast damage from underground bursts are given in Section 9.1.6.



DAMAGE TO BRIDGES BY BURSTS AT LOW HEIGHTS

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CHAPTER 9
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FIGURE 2 & 3

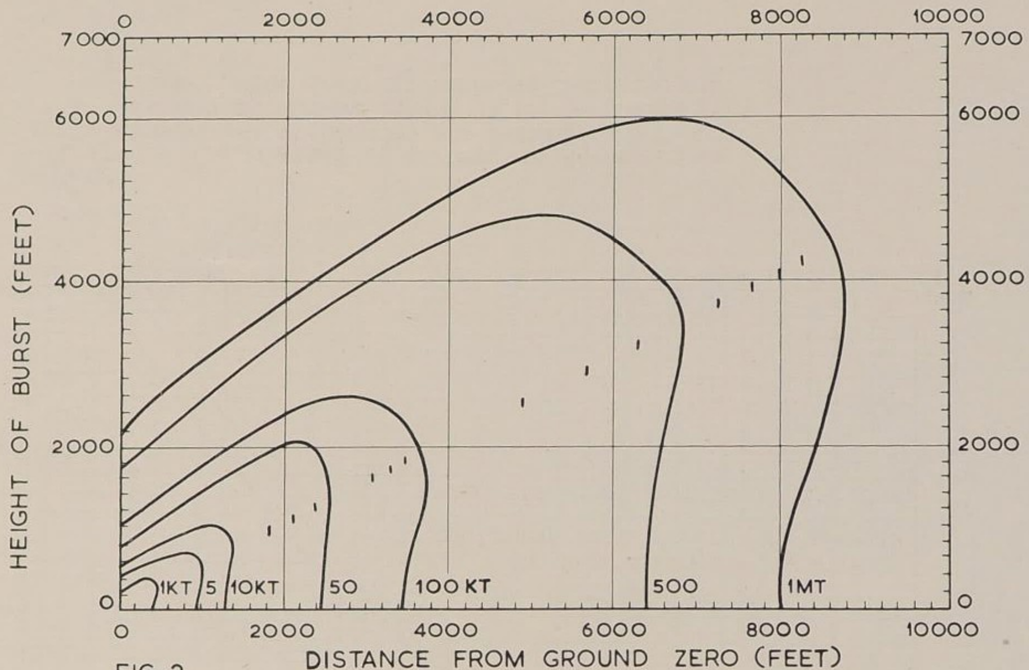


FIG. 2

50% PROBABILITY OF SEVERE DAMAGE. FOR 50% PROBABILITY OF LIGHT DAMAGE SCALE 0·6.P.S.I. DYNAMIC PRESSURE CONTOUR IN CHAPTER 1, SECTION 1.1. TO CONVERT TO OTHER CRITERIA SEE SECTION 9.1.5. FOR DAMAGE DESCRIPTIONS SEE SECTION 9.1.TABLE 1. BLAST STRIKING BETWEEN 45° AND 90° TO LONGITUDINAL AXIS OF BRIDGE. FOR ORIENTATIONS BETWEEN 0° AND 45°, INTERPOLATE LINEARLEY BETWEEN 60% AND 100% OF THE DAMAGE RANGES SHOWN

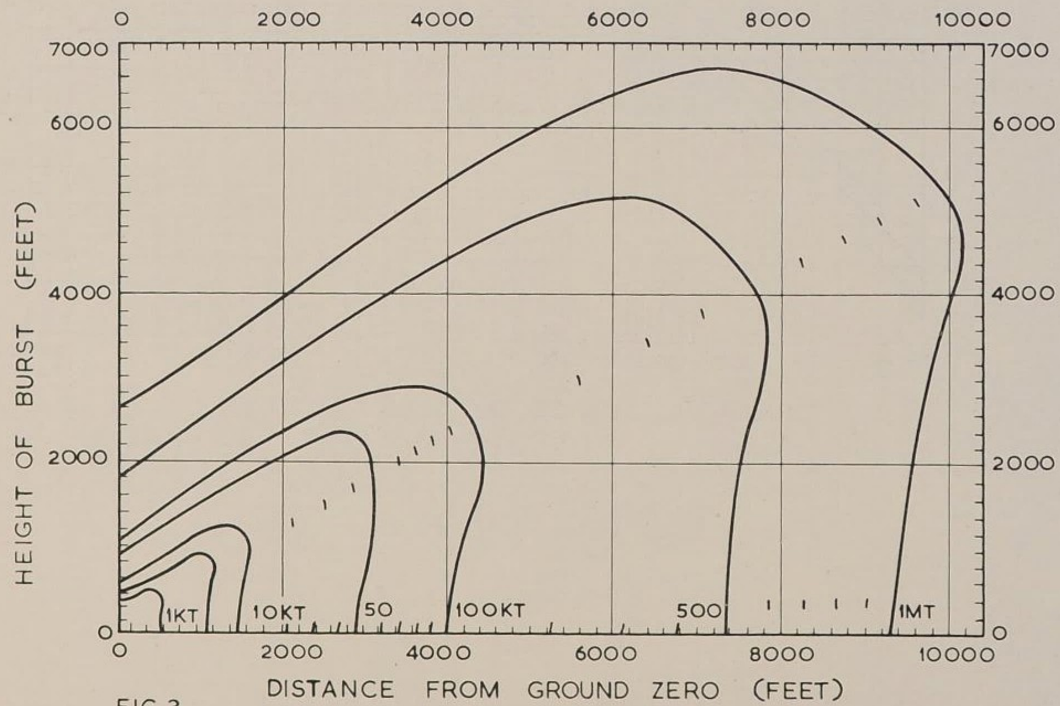
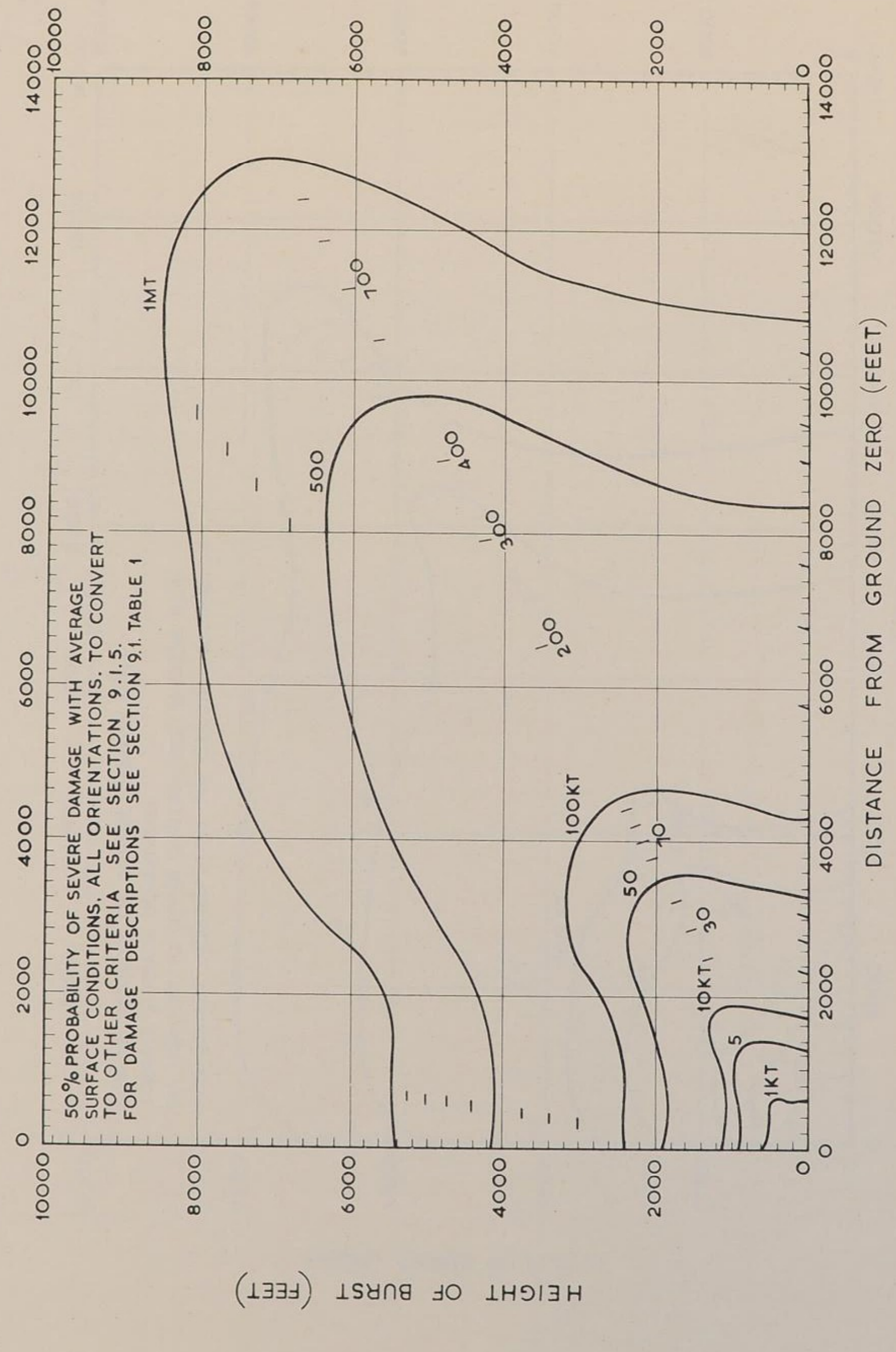


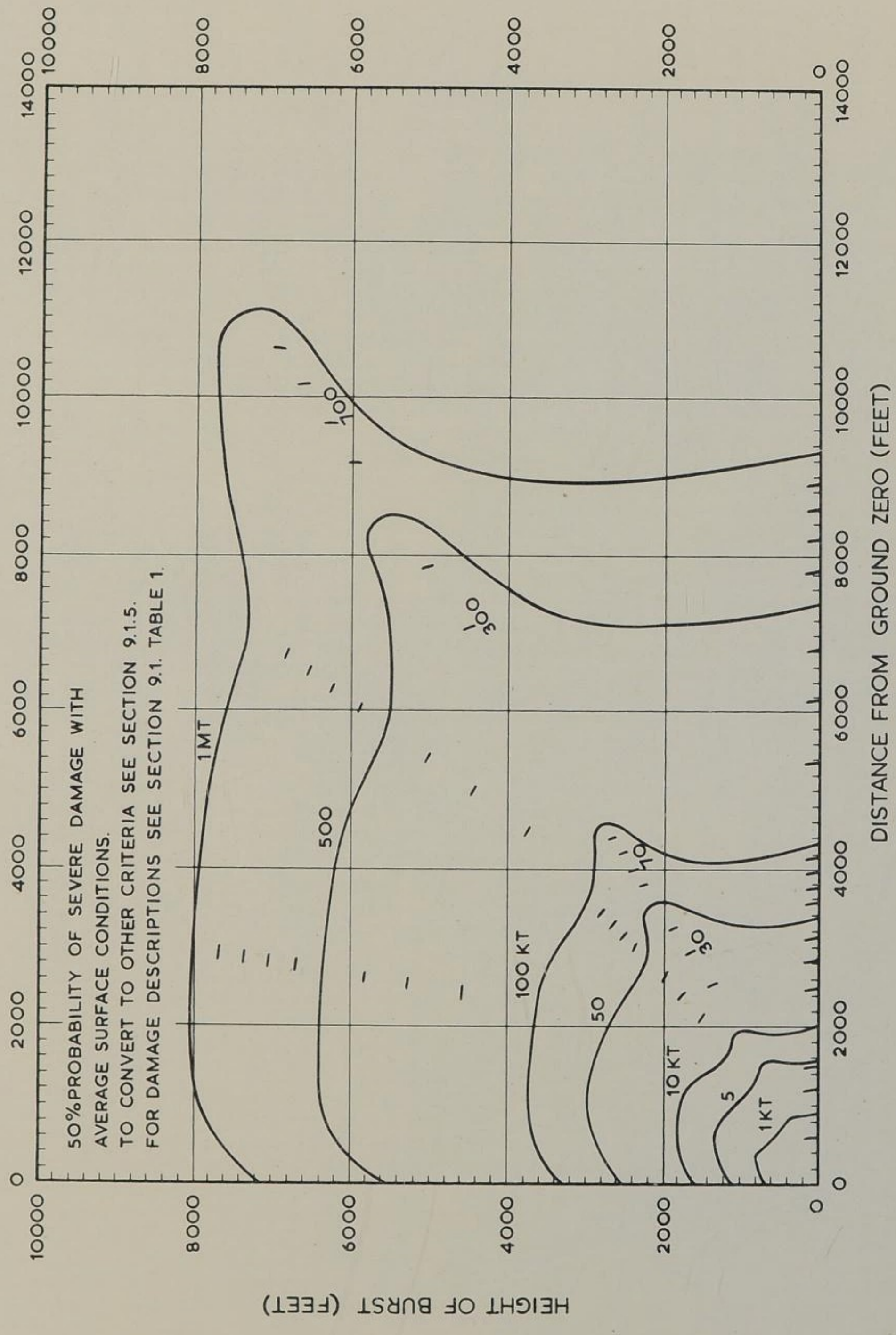
FIG. 3

FIG. 2 DAMAGE TO TRUSS BRIDGES OF 150′-250′ SPAN.

FIG. 3 DAMAGE TO TRUSS BRIDGES OF 250′-550′ SPAN.



DAMAGE TO FLOATING BRIDGES
TYPES M-2 OR M-4



DAMAGE TO FILLED OIL STORAGE TANKS

PART IV - DAMAGE BY CRATERING AND EARTH SHOCK

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Chapter 5. Debris from Surface Bursts

SYMBOLS

A_G = Amplitude of ground wave (feet).

A_L = Amplitude of incident longitudinal wave (feet).

a = Peak acceleration in 'g' units.

$a(t)$ = Ground acceleration as a function of time.

B = Impulse constant for soil.

B_L = Amplitude of reflected longitudinal wave (feet).

B_T = Amplitude of reflected transverse wave (feet).

b = Breadth of building (feet).

D_A = Apparent depth of crater, including backfill (feet).

D_P = Depth of plastic zone (feet).

D_R = Depth of rupture zone (feet).

D_T = True depth of crater without backfill (feet).

d = Depth below surface (feet).

E = Energy of earthquake (Ergs).

E_o = Energy of reference (zero magnitude) earthquake. 2×10^{11} Ergs.

F = Coupling factor (depth).

H_L = Height of lip of crater (feet).

h = Height of building (feet).

I = Impulse (pounds x seconds per square inch).

I_M = Modified Mercalli Intensity.

i = Angle of incidence.

k = Soil constant.

L = Distance of tunnel from weapon (feet).

l = Length of building (feet).

M = Magnitude of earthquake (Richter's Scale).

n = Damping constant in equation of motion of a structure.

p = Free earth peak pressure (pounds per square inch).

R = Distance from weapon (feet).

R_A = Apparent radius of crater, including backfill (feet).

R_C = Radius of crater, backfill unspecified (feet).

R_D = Resistance per unit mass of a structure against deflection.

R_L = Radius of outer lip of crater (feet).

R_P = Radius of plastic zone (feet).

R_R = Radius of rupture zone (feet).

R_T = True radius of crater, without backfill (feet).

r = Angle of reflection of the transverse wave.

t = Time (seconds).

U = Fly velocity (feet per second).

u = Maximum value of horizontal component of surface particle velocity.

V_A = Apparent volume of crater (cubic feet).

V_P = Volume of plastic zone (cubic feet).

V_R = Volume of rupture zone (cubic feet).

V_T = True volume of crater (cubic feet).

v_L = Velocity of propagation of longitudinal wave (feet per second).

v_T = Velocity of propagation of transverse wave (feet per second).

W = Total energy of explosion (kilotons).

x = Displacement of centre of gravity of structure relative to its base.

Δ = Differential displacement between the ends of a building (feet).

ν = Poission's ratio.

ρ = Soil density (pounds per cubic foot).

σ_n = Normal stress (in the direction of propagation).

σ_t = Transverse compressional stress (in the plane of the wave).

τ = Duration of positive phase of blast wave (seconds).

ω_o = Constant in equation of motion of a structure.

PART IV - CRATERING AND EARTH SHOCK

CHAPTER 1 - INTRODUCTION

1.1. General

Energy from nuclear explosions is transmitted to the ground by three main mechanisms. These are:-

(a) Direct ground shock, where energy is transmitted close to Ground Zero and then is propagated by the seismic waves through the ground to the target.

(b) Cratering. Some energy is expended in forming a crater, and this energy is not transmitted to the target unless the target is effectively within the region of the crater.

(c) Ground shock induced by air blast. As the blast wave travels outwards across the ground the hydrostatic pressure is transmitted to the ground, which is forced to move. This pressure and motion can cause damage to a structure.

Note that for near surface bursts these damage mechanisms are generally of interest only in the case of buried targets, because the crater and its lip lie wholly within the region enveloped by the fireball, and air blast and thermal and nuclear radiations are likely to cause total damage to exposed surface targets. Moreover, the optimum depth for crater production represents bursts far deeper than are likely in practice, except in the case of deliberately buried weapons, and the majority of bursts are likely to be of the shallower type in which the cratering and ground shock effects are somewhat reduced. Therefore in this part of the Manual we shall mainly consider underground targets, and divide them into categories, depending on their principal damage mechanisms. In the absence of either a theoretical or an empirical definition of the shock parameter mainly responsible for damage to targets, it is common practice to describe the distances at which damage to such targets occurs in terms of the crater radius and depth. These parameters are therefore discussed briefly in Section 1.2, and the corresponding empirical damage distances listed in 1.6, before proceeding to a more refined treatment in terms of the various earth stress parameters. The latter include the three-dimensional components of particle displacement, velocity, and acceleration, and the associated pressures and frictional forces.

Interest in damage to surface structures is confined to the case of very deep non-cratering bursts. As no full-scale data are available, this case is covered so far as possible by references to studies of damage by earthquakes of shallow origin. This necessitates some inter-comparison of the measures of earthquake intensity and of nuclear weapon yields.

It is emphasised that computation of damage by all the above mechanisms is likely to remain no more than an approximation, owing both to the importance of variations of terrain, and to the almost total lack of accurate full-scale data on which to base more precise empirical scaling rules.

1.2. Dependence of Effects on Burst Position and Soil Type

The dependence of the phenomena of cratering and earth shock upon the terrain and upon the position and size of burst are discussed in detail in References (1) to (4). For convenience there follow brief descriptions of the effects produced in an "average" soil by bursts at different scaled depths, beginning with one so deep that no crater is formed at the surface and ending with the highest air bursts capable of producing ground effects. Appendix A.

In the case of deep bursts, - i.e. more than $300W^{\frac{1}{3}}$ feet down* -, there is no venting at the surface. A cavity, known as a camouflet, is formed. No data from nuclear explosions at such depths are yet available. Much smaller scale H.E. charges have been found to radiate about two-thirds of their energy away from the vicinity of the explosion in the form of plastic and elastic stress waves, leaving about one third of the blast energy available for camouflet formation. The fraction of the total energy of a nuclear explosion which would become available for camouflet formation is not known, but about 30% is considered a likely figure. In this case the radius of the camouflet in average soil would be reduced from 160 $W^{\frac{1}{3}}$ feet for H.E. to roughly 100 $W^{\frac{1}{3}}$ feet, for nuclear weapons. In practice, it might differ by a factor of two either way, depending upon the type of rock and its water content. It will be apparent that in most localities the nature of the ground will change considerably over depth variations of this magnitude, so that practical assessments are likely to be imprecise. See Appendix A.

Bursts less than some 200 $W^{\frac{1}{3}}$ - 300 $W^{\frac{1}{3}}$ feet down may break through the surface and vent to the air. The resulting crater increases in size with decreasing burst depth, until it reaches a maximum size for burst depths of 60 $W^{\frac{1}{3}}$ - 120 $W^{\frac{1}{3}}$ feet. This maximum size is given as about 140 $W^{\frac{1}{3}}$ feet radius and about 100 $W^{\frac{1}{4}}$ feet deep, "in average dry soil or soft rock". Above 60 $W^{\frac{1}{3}}$ feet, the crater size decreases with burst depth to 55 $W^{\frac{1}{3}}$ feet radius and about 27 $W^{\frac{1}{4}}$ feet depth for a surface burst. Ground shock effects are reduced, as a proportion of the bomb energy now escapes from the surface as air blast, thermal energy, and kinetic energy of bomb cloud and crater debris. On the other hand it is at this point that the third mechanism of damage may begin to assume importance for buried targets. The air blast wave, being propagated with much lower losses than the ground shock, may proceed to larger distances and then give rise to induced ground shock by virtue of its passage over the surface of the ground.

Both cratering and direct ground shock effects are generally negligible as damage mechanisms for heights of burst greater than about 20 $W^{\frac{1}{3}}$ feet, i.e. about one tenth of the fireball radius, although the relative values of blast, thermal and nuclear radiation effects continue to change above this height. Of the blast effects, only shock remains important for burst heights greater than one third of the fireball radius. It seems probable that the mechanism of crater formation changes, for heights of burst in the region of 10 $W^{\frac{1}{3}}$ feet above the surface, from a process of push-out, throw-out and scouring, to one of compression and scouring. The crater radius therefore goes through a minimum of about 30 $W^{\frac{1}{3}}$ feet at this height, and then increases with height of burst up to about 80 $W^{\frac{1}{3}}$ feet, but above 20 $W^{\frac{1}{3}}$ feet the depth of the crater formed is so very small that the overall effect is not usually significant.

For convenience of reference, crater radius and depth as a function of yield for various heights and depths of burst are shown in Figures 1 and 2 respectively. These apply to dry soil, and are derived from References (1), (2), and (4).

* W = total energy of explosion, in Kilotons. For sealing laws see section 1.3 below and Part I, section 6.

The influence of soil type

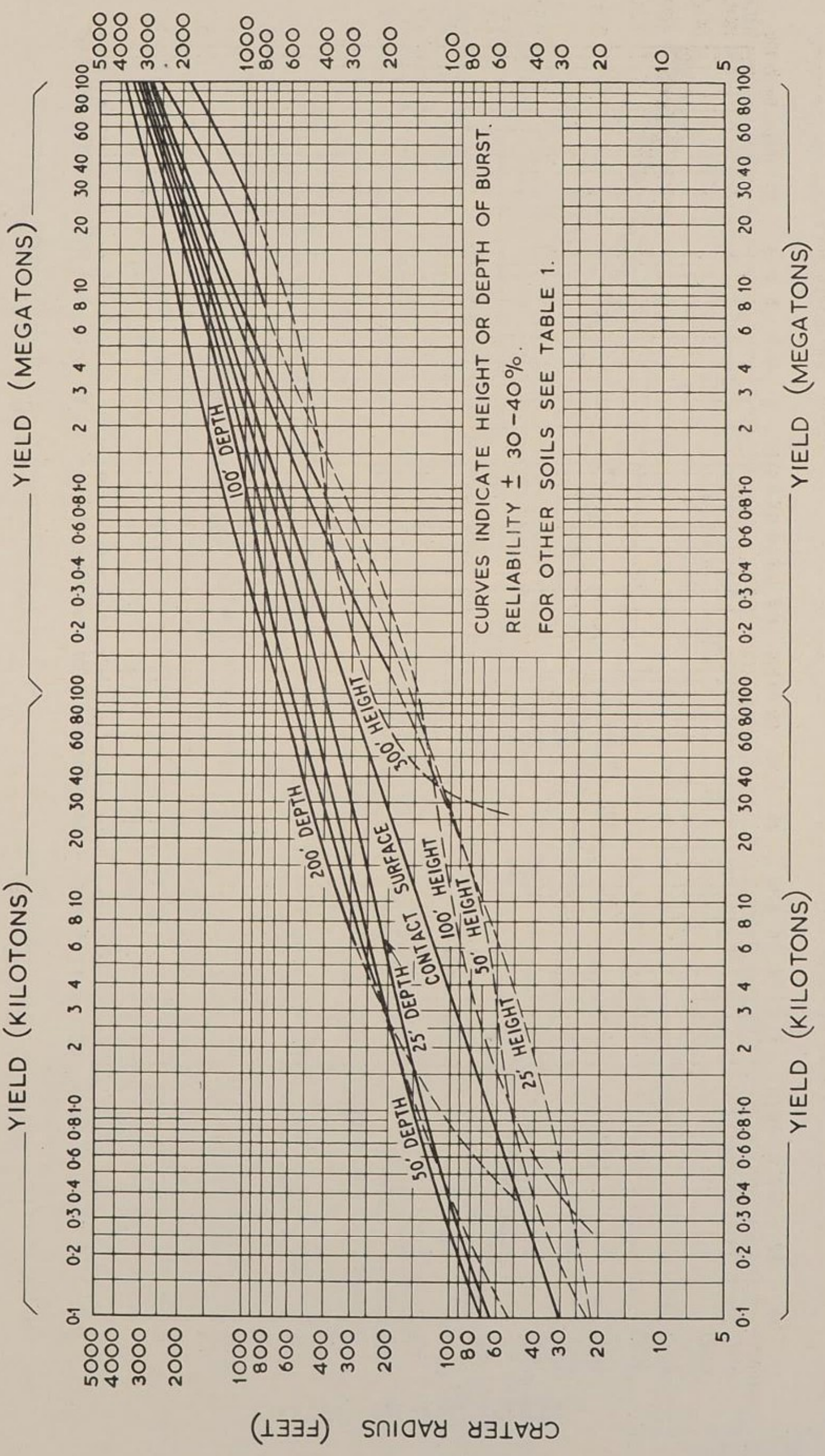
The influence of soil type on the various crater and ground shock parameters is discussed in detail in References (1), (2), (3) and (4). The variations of crater radius and depth with soil type are given in Table 1, in the form of approximate multiplying factors to be applied to "dry soil" data.

Table 1 - Influence of Soil Type on Crater Dimensions

Soil Type	Example	Factor for Crater Radii	Factor for Crater Depths
Hard rock	Maralinga[+]	0.8	0.8
Dry soil or soft rock	Nevada	1.0	1.0
Moist or damp soil	Pacific, on reef	1.5	1.5
Saturated soil	Pacific, on sand	2.0	0.7

The above factors are used to scale the dimensions of the crater and surrounding lip, rupturing and plastic zones. The symbols used for these parameters in this Manual are shown in Figure 3.

[+]For further details of Maralinga site, see Chapter 2, Section 2.2, Table 2.



CRATER RADIUS IN DRY SOIL OR SOFT ROCK

PART IV
CHAPTER 1
SECTION 1.2
FIGURE 2

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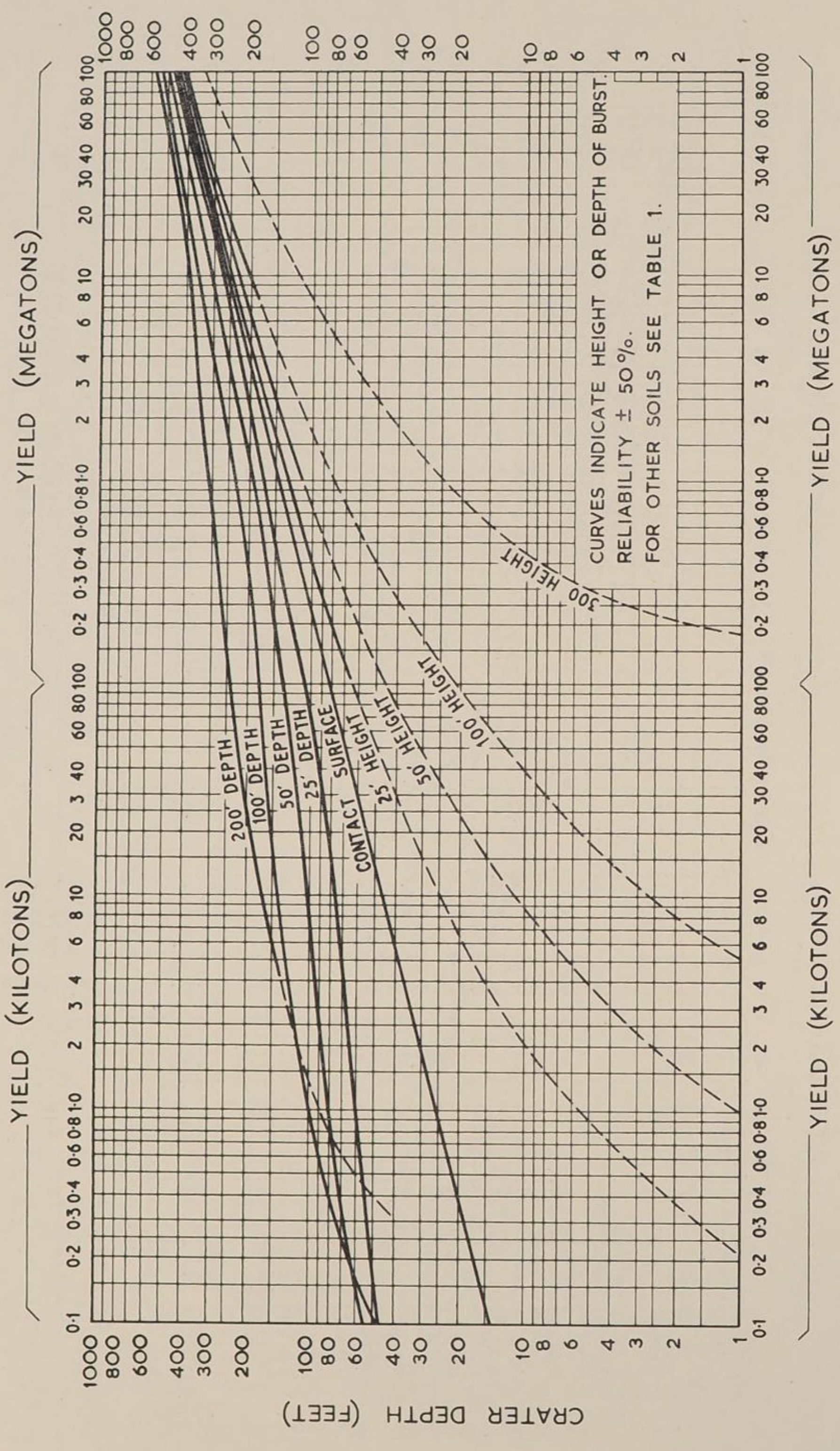
D.N.W.
MAY 1958



CRATER DEPTH IN DRY SOIL OR SOFT ROCK

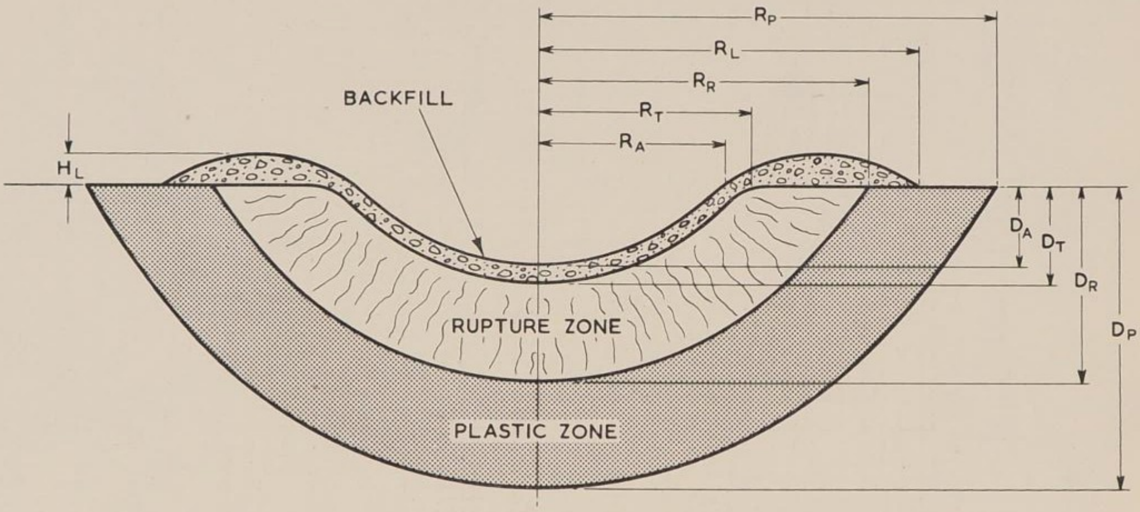
CONFIDENTIAL

NOTE:–

CRATER RADII ARE MEASURED AT THE ORIGINAL GROUND LEVEL.

CRATER DEPTHS AND LIP HEIGHTS ARE MEASURED RELATIVE TO THE ORIGINAL GROUND LEVEL.

UNCERTAINTIES OF TERRAIN TEND TO MASK THE DISTINCTION BETWEEN TRUE AND APPARENT DIMENSIONS. WHEN NO DISTINCTION IS FEASIBLE, R_C AND D_C ARE USED FOR CRATER RADIUS AND DEPTH RESPECTIVELY.



R_A = APPARENT RADIUS OF CRATER, INCLUDING BACKFILL.

R_T = TRUE RADIUS OF CRATER WITHOUT BACKFILL.

R_R = RADIUS OF RUPTURE ZONE, APPROXIMATELY $1{\cdot}5\ R_A \pm 25\%$

R_L = RADIUS OF OUTER LIP OF CRATER, APPROXIMATELY $2\ R_A \pm 25\%$

R_P = RADIUS OF PLASTIC ZONE, SOMEWHAT GREATER THAN R_L FOR MOST SOILS BUT PRACTICALLY NON-EXISTENT FOR ROCKS.

H_L = HEIGHT OF LIP OF CRATER, APPROXIMATELY $0{\cdot}25\ D_A \pm 50\%$

D_A = APPARENT DEPTH OF CRATER, INCLUDING BACKFILL.

D_T = TRUE DEPTH OF CRATER WITHOUT BACKFILL.

D_R = DEPTH OF RUPTURE ZONE.

D_P = DEPTH OF PLASTIC ZONE.

V_A = APPARENT VOLUME OF CRATER (ASSUMED PARABOLOIDAL)
$= \pi\ R_A{}^2 .\ D_A / 2.$

V_T = TRUE VOLUME OF CRATER (ASSUMED PARABOLOIDAL)
$= \pi\ R_T{}^2 .\ D_T / 2.$

V_R = VOLUME OF RUPTURE ZONE.

V_P = VOLUME OF PLASTIC ZONE.

CRATER PARAMETERS

Effects Produced at Underground Shot
Nevada, 1958

The following account of a small underground nuclear burst is taken from a lecture by Dr. Willard F. Libby, Commissioner of the U.S.A.E.C., May 26th, 1958. It is included here in amplification of the second paragraph of Section 1.2 of this chapter.

Last of the present list of peaceful uses is the non-military applications of nuclear explosions. This is known as Project Plowshare. It was born out of the war-like atom in that a desire to reduce the obnoxious radioactive fallout from nuclear weapons' tests led to the first try - the Rainier shot of Operation Plumbbob.

Rainier is the underground shot - 1.7 KT - which was fired at 10 o'clock Pacific daylight time on September 19, 1957 (the exact time was 9 hours, 59 minutes and 59.45 seconds). The site of the firing of course, was the Nevada Proving Grounds, and the exact co-ordinates were 37° 11' 44.80" N latitude, 116° 12' 11.35" W longitude. The bomb was located in the centre of a room approximately 6' x 6' and 7' high. The entrance was plugged by sandbagging the curved corridor.

The firing was accomplished from a control point located at a distance of 2.5 miles from the point of detonation. At this location a weak ground wave was felt by a few people and a muffled explosion was heard. The immediate visible effects of the explosion were the ripple which spread over the face of the mesa as the pressure wave reached the surface and broke loose of some of the rocks comprising the crown of the mesa, which then rolled down the slopes of the mountain.

On making a detailed survey, except for the mentioned loosening and falling of rocks from the crown and some superficial cracking of the surface directly over the point of detonation, no other damage to the mountain was apparent. Detailed radiological surveys of the area revealed that there had been no detectable venting of radioactive materials at any point.

The shot tunnel was entered, and the door at 575 ft. from the point of detonation was reached four hours after detonation. Except for occasional spalls and a shift of a few inches of one bedding plane at approximately 1100 ft. from the point of detonation, the tunnel was intact. The alpha, beta, and gamma radiation levels were the same as those read read prior to the detonation. The background gamma radiation level in the tunnel is 0.04 mr/hour.

For operational reasons it was decided to wait a few days before opening the inner door at 575 feet to survey further the effects of the explosion. This was done on September 24, 1957, and the tunnel penetrated to within 200 feet of the centre of detonation.

Except for the final 500 feet, the tunnel was relatively undamaged. However, beginning about 200 ft. from ground zero, the tunnel was closed off completely. The curved end of the tunnel was especially designed to assure this type of sealing of the tunnel. This aspect of the tunnel design was completely successful as proved by the fact that the radiation level at all points did not exceed the background level.

In view of the uncertainties associated with the distribution of energy around the point of detonation and the possibility of the existence of cavities at high temperature and pressure, it was decided to vent the cavity by drilling from the top of the mesa. The drilling system with

built-in safety features was designed for remote operation in the event that the drill penetrated a high pressure region. This turned out to be very time-consuming because of the fact that beneath the hard cap of the mesa (about 250 ft. thick) there is a layer 600 ft. thick of loosely consolidated material. However, on November 1, the drill broke into a cavity at 385 ft. above the point of detonation, and the depth of this cavity was found to be 25 ft. Photographs made in the cavity indicated broken tuff and sand had collected in the bottom of a roughly conical cavity. The volume of which was estimated to be of the order of 15,000 cubic feet.

Subsequently, drilling was pushed down to a depth a little below that at which the shot was fired and no cavity was found in this region.

Now that it was known to be safe to drill from within the tunnel, all drilling operations were shifted to this location. A series of holes were drilled and logged for temperature and radioactivity.

The temperature reached a peak value of 45°C at a radius of 60 ft., and then decreased to a fairly constant value of 33°C ± 2° from 35 ft. in to zero. In some holes, temperatures as high as 90°C were observed. (At this altitude water boils at about 94°C.) A rough calculation of the total thermal energy contained in the heated volume gives one-half of the total energy release of the device. When the total balance is measured, the thermal content is expected to comprise a much larger fraction.

The radioactivity of the bomb is contained in some 700 tons of active material, the general appearance of which is glassy with bubbles and containing many inclusions of granular tuff of various degrees of fusion. It has a dark colour.

With these numbers and drilling results, it is possible to reconstruct the general geometry of the explosion.

The general sequence of the events that occurred shortly after detonation may now be constructed. It appears that a spherical cavity having a radius 55 ft. was formed by vaporization of rock, the inner surface of which was fused tuff. The thickness, t, of the shell was, then, based on the volume of melted material, 10 cm. or 4 inches. The shell collapsed probably immediately after the vapour inside cooled and the supporting pressure dropped. Crushed rock then moved in radially and the roof fell in. The collapse proceeded vertically until uncrushed rock was reached which was of sufficient strength to support the cavity roof. The broken once-melted shell containing the radioactive products was subsequently distributed in a layer of broken tuff a few feet thick. It cooled very quickly by mixing with the cooler tuff and by the convective cooling of the water with which the porous rock was nearly saturated.

A rough estimate of the shock pressure as a function of a radial distance from the detonation can be made. The pressure on the wall of the room as the shock entered the rock was about six megabars as calculated from the energy density at that time. At 130 ft., the pressure had dropped to the crushing strength of the rock under dynamic loading - estimated as 1 or 2 kilobars. The shock pressure required to melt the rock is probably greater than 10^5 bars, so the fused material which is not found beyond 55 ft. from the centre was originally contained in a sphere of radius 10 to 15 feet about the point of detonation. Using a radius of 15 ft., the calculated mass of material melted by the shock would be 10^9g, which is consistent with the value derived from the radiochemical data (7×10^8g). The amount of rock crushed is estimated at 0.4 million tons.

1.3. Scaling Laws

In this chapter use is made of the Scaling Laws already described in Part 1, Section 6, whereby corresponding parameters of two explosions may be related in terms of the ratio of their yields. Thus, if subscript o denotes the values as for a reference explosion of total power W_o kilotons the values for another explosion of total power W kilotons are found as follows:-

Energies	scale as (W/W_o)
Distance and Times	scale as $(W/W_o)^{\frac{1}{3}}$
Accelerations	scale as $(W/W_o)^{-\frac{1}{3}}$
Velocities and Densities	are invariant.

Note that phenomena which are critically dependent upon gravity do not scale according to these rules, since it is impossible to change gravity with weapon yield. Thus, effects such as those due to the hydrostatic pressure at appreciable depths in the ground give rise to important limitations in the application of experimental data. In practice crater radii are taken as scaling with $W^{\frac{1}{3}}$, and crater depths as scaling with $W^{\frac{1}{4}}$, to a sufficient degree of approximation.

1.4. Relationship to High Explosive Charges

Many of the results quoted later have been obtained by applying the above scaling laws to the results of experiments with small H.E. charges. This is legitimate provided one assumes that a nuclear weapon of yield W produces effects comparable with those due to a certain weight of H.E., American full-scale evidence suggests that, for weapons exploded on the ground, a weapon of total yield W kilotons is equivalent in its direct ground shock and cratering effects to the effects produced by 0.14 W kilotons of T.N.T. Air-induced ground shock is equivalent to that produced by 0.45 W kilotons of T.N.T. For a weapon exploded more than $200^{\frac{1}{3}} W^{\frac{1}{3}}$ feet in the air, the action on the ground will be almost entirely due to air blast, and in this case the weapon is also equivalent in its cratering and ground shock effects to the effects produced by 0.45 W kilotons of T.N.T. exploded in the same position. The transition between these two extreme cases is somewhat complex, and present data do not permit a full description in terms of H.E. This limits the applicability of scaled H.E. data, but does not invalidate the application of data from nuclear tests.

1.5. Types of Structure

The presence of the free surface of the ground has a profound effect on the stress waves propagated from an explosion. The normal and tangential components of stress must be zero at the surface, and therefore a structure close to the surface will not be subject to a hydrostatic pressure due to the passage of the wave. This permits us to draw a broad distinction between surface and sub-surface target structures. So far as ground effects are concerned, surface structures such as those considered in Chapter 4 are those structures for which inertial and differential movement effects are all-important. They are, in fact, shaken down. Sub-surface structures such as those considered in Chapters 2 and 3 are those structures to which the damage is done by compressional wave from the explosion, and to which inertial forces are only of secondary importance. They are squeezed to destruction. These two cases represent the extreme conditions of a highly complicated phenomenon, and the two effects (shaking and squeezing) would of course merge into each other for intermediate targets.

Sub-surface targets may again be divided into two classes. Those in soft soils whose main strength is in their walls, which may, for example, be reinforced concrete. This type is considered in Chapter 2. The other type, which for convenience we call tunnels, are structures in hard, rock-like media which derive their strength from the medium itself and may have only a weak, thin retaining wall. Tunnels are considered in Chapter 3.

1.6. Empirical Damage Distances

Because the mechanism of damage to underground structures from ground shock and cratering is dependent upon several more or less unrelated variables such as the size, shape, flexibility, and orientation of the structure with respect to the explosion, and also upon the characteristics of the soil or rock, it has not yet proved possible to define, either theoretically or empirically, the shock parameter causing damage. There is however, considerable experimental evidence from studies using high explosive charges indicating that the parameters involved in producing damage can be adequately related to the crater radius, except for burst heights greater than 5 $W^{\frac{1}{3}}$ feet, in which case the crater depth becomes small. Therefore, except for burst heights greater than 5 $W^{\frac{1}{3}}$ feet, the criteria for structural damage and ground shock may be given in terms of crater radii, as derived from Section 1.2, Figure 1, or Reference 1.

For purposes of empirical estimation of earth shock damage from contact or sub-surface bursts, underground structures may be divided into categories as follows:-

(i) Relatively small highly resistant targets in soil:- This type, which includes reinforced concrete fortifications, can probably be damaged only by acceleration and displacement of the structure as a whole. For damage distances see Table I below.

(ii) Moderate size, moderately resistant targets:- These targets are damaged by soil pressure as well as by acceleration and bodily displacement. The iso-damage surface for structures at depths less than 20 $W^{\frac{1}{3}}$ feet can be approximated by a segment of a hemisphere whose centre is ground zero, and whose radius is damage distance given in Table I below. For structures deeper than 20 $W^{\frac{1}{3}}$ feet, the damage distances are somewhat less than the values given.

(iii) Long, relatively flexible targets:- These include buried pipes and tanks, which are likely to be damaged in regions where large soil strains exist. Underground structures may also be damaged by shearing off connecting services such as those for ventilation, water, power, and access. In this case, relative earth displacement is an important factor in producing damage. Damage of this type may extend out to about $2\frac{1}{2}$ crater radii in some soils if the connections are of brittle material and are rigidly attached to the structure.

Table I

Damage Distances for Underground Structures

Type of Structure (as defined above)	Damage Category	Distance from Surface Zero	Nature of Damage
(i) and (ii)	Severe	$1\frac{1}{4}\ R_C$	Collapse or severe displacement
	Moderate	$1\frac{1}{4}\ R_C - 2\ R_C$	Shock damage to interior equipment
	Light	$2\ R_C - 2\frac{1}{2}\ R_C$	Severance of brittle external connections; slight cracking at structural discontinuities.

Table I (continued)

Type of Structure (as defined above)	Damage Category	Distance from Surface Zero	Nature of Damage
(iii)	Severe	$1\frac{1}{2}\ R_C$	Deformation and rupture
	Moderate	$1\frac{1}{2}\ R_C - 2\ R_C$	Slight deformation with some rupture
	Light	$2\ R_C - 3\ R_C$	Failure of connections (use the higher value in the case of radial orientation of connections)

(iv) Orientation sensitive targets:- Targets such as gun emplacements may be susceptible to damage from small permanent displacements, or tilting. Heavy machinery and other items susceptible to small displacements, if located in underground structures, receive moderate damage out to about $2\frac{1}{2}$ crater radii, and are likely to be unusable without realignment.

(v) Rock tunnels:- Damage to such targets from an external explosion is caused by the tensile reflection of the shock wave from the rock/air inter-face, except when the crater breaks through into the tunnel. Larger tunnels are more easily damaged than smaller ones. However, no correlation between damage and tunnel size or shape is known. Damage to tunnels is discussed in Chapter 3, Section 1.

(vi) Structures close to the surface:- For empirical data on light earth-covered structures and earthworks within about 8 feet of the surface, see Part III, Chapter 9, Sections 9.3.1 and 9.3.2.

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(3) Effects of Nuclear Weapons. U.S. Government Printing Office 1957. Unclassified.

(4) Cratering and Ground Shock from Nuclear Weapons. AFSWP/Tripartite Conference Paper August, 1957. Confidential/Atomic

(4a) Letter SWPBS 924 of 25th Feb., 1958, in amplification of Reference 4, Figures 8 and 9.

(5) Stress Waves in Solids. Kolsky.

D1/57 December 1957

Part IV
Chapter 2
Section 2.1

CHAPTER 2 - UNDERGROUND STRUCTURES IN SOIL

2.1 Introduction

This section deals with the forces acting on an underground structure. The structure is assumed buried at some depth in soil, and the forces acting on it result mainly from the pressures set up in the ground. In the case of weapons exploded close to the surface, the predominant loading on a structure will be due to the air blast pressure transmitted through the ground, but for weapons exploded at a depth of greater than 40 W^3 feet the loading is primarily caused by the pressure in the stress waves that are propagated through the ground from the centre of the explosion. American workers (References (1) and (2)) found that in this situation the pressure wave was a single pulse. This result is not substantiated by British workers (Reference (3)), who found that apart from the air blast excited shock, the general nature of the surface motion is independent of the depth of the weapon. The difference is possibly due to the fact that the Americans originally measured hydrostatic pressure at some depth below the surface in a water-filled hole, whereas the British workers were concerned with the motion of the surface itself. It should be noted in this connection that pressure is an artificial concept when describing stress in a solid such as the earth. The stress at any point should be described by six independent components for a general three-dimensional solid. This number reduces to three if we assume radial symmetry about the vertical axis through the centre of the explosion. The American results, however, provide the only available basis for a study of damage to underground structures. Certain recent work is summarised in Reference (4).

References

(1) Final Report on the Effects of Underground Explosions, C.W. Lampson. N.D.R.C. Report No. A-479. O.S.R.D. Report No. 6645, March, 1946.

(2) Underground Test Programme. Engineering Research Associates. Final Report Vol. 1. Soil. (Confidential/Discreet)

(3) Measurement of Ground Shock in Unconsolidated Clay, Part 1. Surface Movement due to a Charge Detonated on the Ground. A.W.R.E. Report O-20/54. (Confidential/Discreet)

(4) Cratering and Ground Shock from Nuclear Weapons. A.F.S.W.P. Tripartite Conference Paper, September, 1957. (Confidential/Atomic)

(5) Measurement of Ground Shock and Crater. Operation Buffalo. A.W.R.E. Report T37/57. (Secret/Atomic)

2.2 Free Earth Pressures

Note.- For list of symbols see Preliminary, Page 2, of this Part.

In this section the pressures set up in the ground remote from any structure are described. The most detailed series of measurements of earth pressures was carried out in America by Lampson - Reference (1). Applying his results, which were obtained using H.E. charges, to atomic weapons, we may write the pressure (p) at distance R for depths greater than about 200 $W^{\frac{1}{3}}$ feet, as:-

$$p = FkWR^{-3} \qquad 2.2.1$$

This pressure is of the nature of an added hydrostatic pressure. The variation of the coupling factor (F) with scaled weapon depth is shown in Figure 1. This curve is only approximate, since it has been necessary to incorporate very uncertain data on explosive equivalence as a function of depth. The soil constant (k) varies widely from soil to soil and depends on the state of any given soil (e.g. moisture content) at the time of the explosion. The value of the constant was found to be correlated with the velocity of compressional waves in the ground, the so-called seismic velocity, by the relation:-

$$k = 2.5\rho v_T^2 \qquad 2.2.2$$

A list of soil constants is given in Table I for some typical soils.

TABLE I - Typical Soil Constants

Soil Type	Pressure Constant, k	Impulse Constant, B
Loess	2.2×10^8	4×10^6
Loam	5.6×10^8	12×10^6
Silty Clay	1.4×10^9	14×10^6
Clay-unsaturated	4×10^9	16×10^6
Clay-saturated	2.8×10^{10}	16×10^6

The pressure wave consists essentially of a single pulse, the shape and duration of which vary with distance from the weapon. The parameter which takes into account the pressure, duration, and shape of the pulse, is the impulse, which is defined as:-

$$I = \int_0^\tau p.dt$$

Lampson's results applied to nuclear explosions may be written in the form:

$$I = FBW^{7/6} R^{-5/2} \qquad 2.2.3$$

Values of the impulse constant (B) are given in Table I above for typical soils. B can be related to the seismic velocity (v_L), within an accuracy of 35% by the expression:-

$$B = 50\rho v_L \qquad 2.2.4$$

For generalised data on peak particle displacement, velocity, and acceleration as functions of distance from surface bursts, see M.E.A.W., Chapter 2, Data Sheet 2.4. Some full-scale British measurements at Maralinga are reported in Reference (4).

As the terrain at Maralinga is somewhat unusual, details of its physical characteristics have been derived from Reference (4), and are given in Table II.

Table II

P Physical Characteristics of the Rocks in the Geological Section at Maralinga

Depth of Layer	Type of Rock	Density gm/cc	Velocity (ft/sec.)		Characteristic Impedance for P Waves c.g.s. units	Young's Modulus c.g.s. units
			P Waves (longitud-inal)	S Waves (trans-verse)		
0/15 feet	Travertine limestone	2.7	5500 to 8500	-	5.8×10^5	1.2×10^{11}
thence to 75-80 feet	Sand under-lying Travertine	2.0	2200 to 2700	-	1.5×10^5	0.3×10^{10}
thence to 200 feet	Sand and Clay	2.2	4300	-	2.9×10^5	2.7×10^{10}
thence to 1800 feet	Sandstone and/or Shales	2.5	11000 to 12000	8300 to 8600	8.8×10^5	3.1×10^{11}
tens of miles	Granite or Metamorphic Basement or limestone	2.7	19000	-	15.8×10^5	7.7×10^{11}

References

(1) Final Report on Effects of Underground Explosions, C.W. Lampson. N.D.R.C. Report No. A-479. O.S.R.D. Report No. 6645, March, 1946.

(2) Effects of Atomic Weapons. U.S. Government Printing Office, 1950. pp. 413-423

(3) Manual on The Effects of Atomic Weapons (Chapter 2). A.W.R.E. (Secret/Atomic/U.K. Eyes Only)

(4) Operation 'Buffalo'. Measurements of Ground Shock and Crater. A.W.R.E. Report T37/57. (Secret/Atomic)

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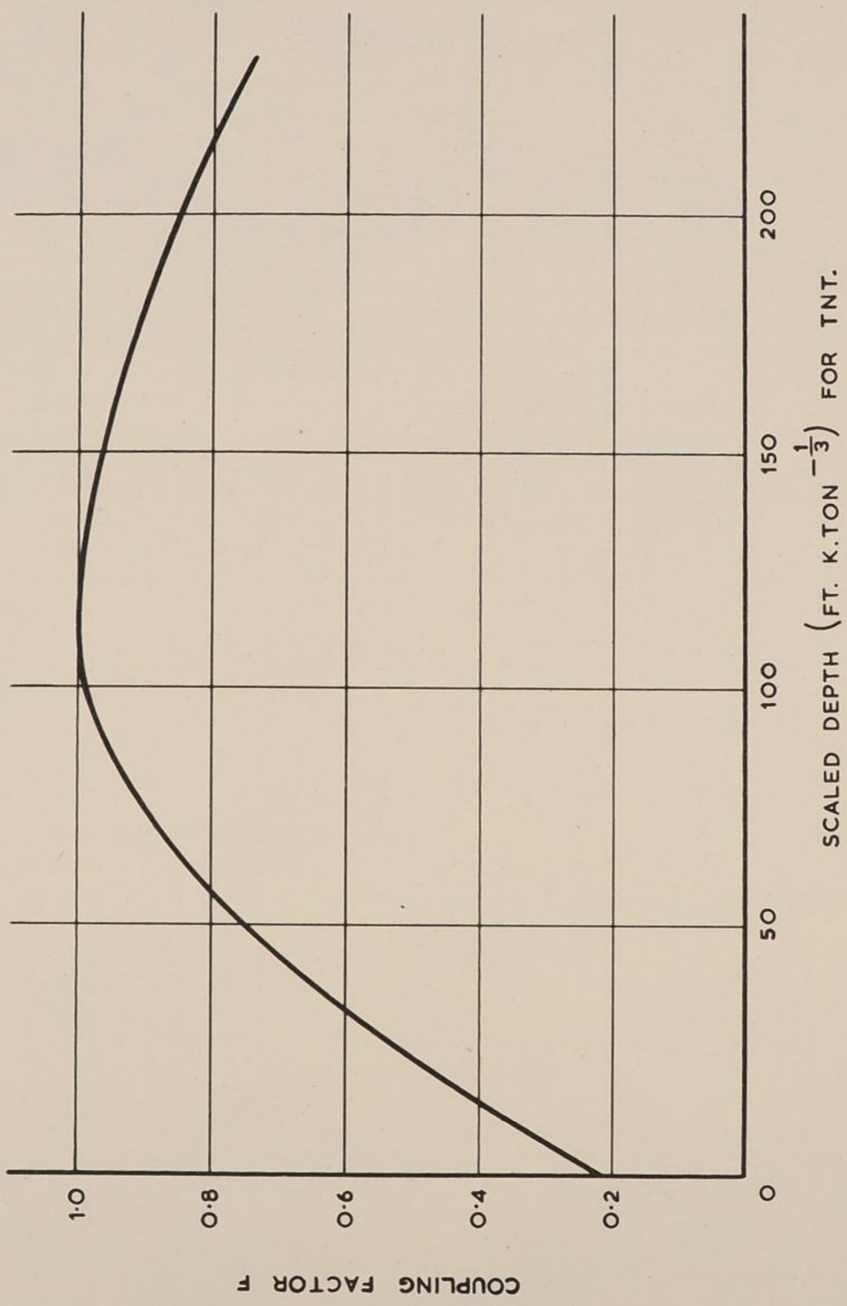


HIGH EXPLOSIVE COUPLING FACTOR
AS A FUNCTION OF WEAPON DEPTH

CONFIDENTIAL

2.3. Structural Forces

When the stress wave from an explosion reaches an underground structure, the reactions of four distinct forces can be distinguished:-

(i) Pressure on the front face;

(ii) pressure on the rear face;

(iii) inertial forces;

(iv) frictional forces

Pressure on the front face - In general, the pressure on the front face of the structure rises to a value of about twice that in the incident wave in free earth. The general shape of the pulse is of the same form as the incident wave, but the duration may be somewhat greater.

Pressure on the rear face - The pressure on the front face of the structure causes it to move away from the explosion, and this motion is resisted by compressive and inertial forces set up in the soil at the back face. Although it is difficult to analyse these forces in detail, their magnitude approximates only 1/10th of the forces on the front face. Figures 1 and 2 show the general nature and the time variation of these forces for two typical experiments with model scale H.E. Charges.

Inertial forces - As the pressure builds up on the front face, the structure is accelerated. The inertial forces on the structure may be calculated in elementary manner by the usual formula:

Force = Mass of structure x Acceleration of structure

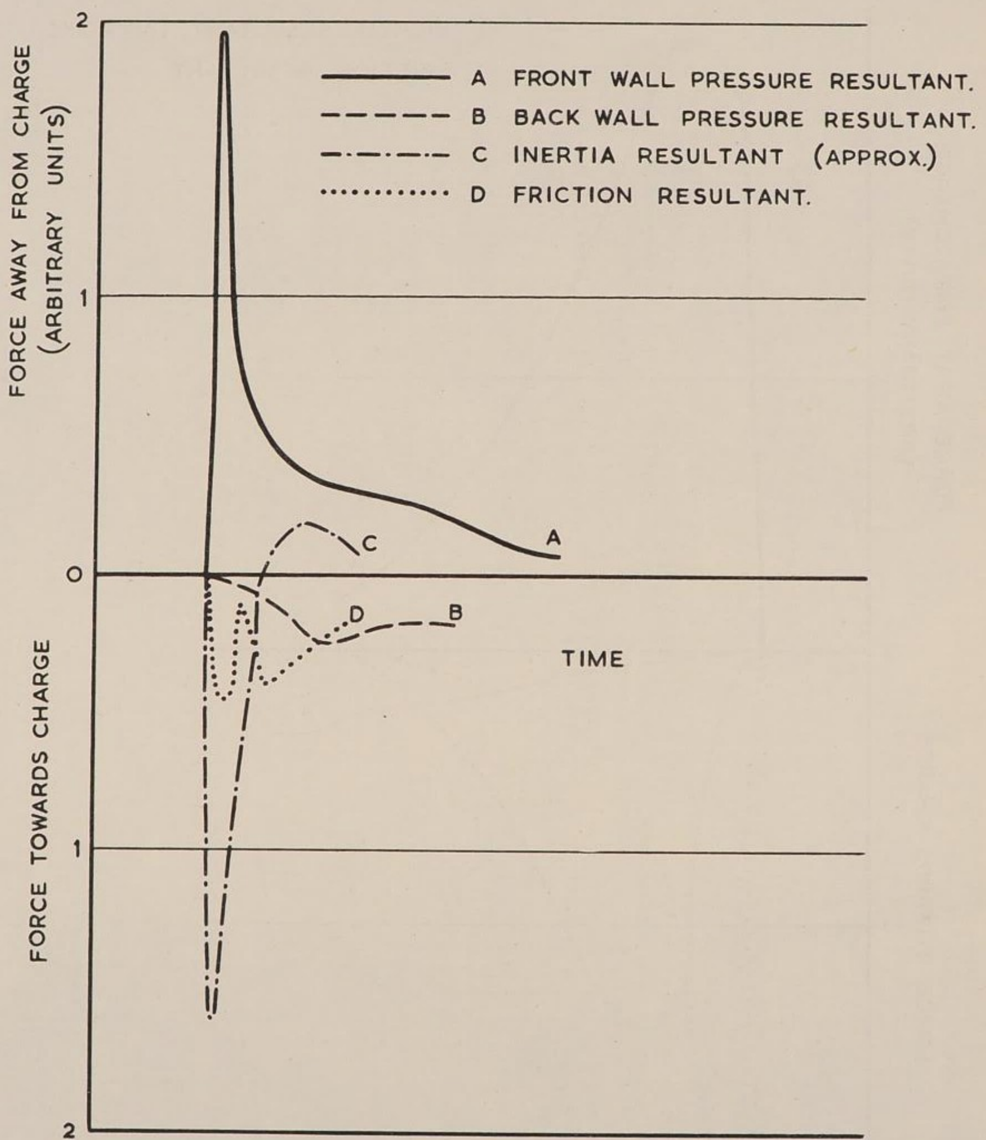
The inertial forces in two typical cases are also shown in Figures 1 and 2.

Frictional forces - The motion of the structure relative to the earth is also resisted by frictional forces, which act on the side walls. No adequate theory is available to predict these forces, but the forces acting in the two cases under consideration are included in Figures 1 and 2, which concern models in dry sand and in dry clay respectively.

References

(1) Final Report on The Effects of Underground Explosions, C.W. Lampson N.D.R.C. Report No. A-479. O.S.R.D. Report No. 6645, March, 1946

(2) Underground Test Programme. Engineering Research Associates. Final Report, Vol.1. Soil. Confidential/Discreet



TYPICAL FORCES ACTING ON MODEL STRUCTURE
BURIED IN DRY SAND

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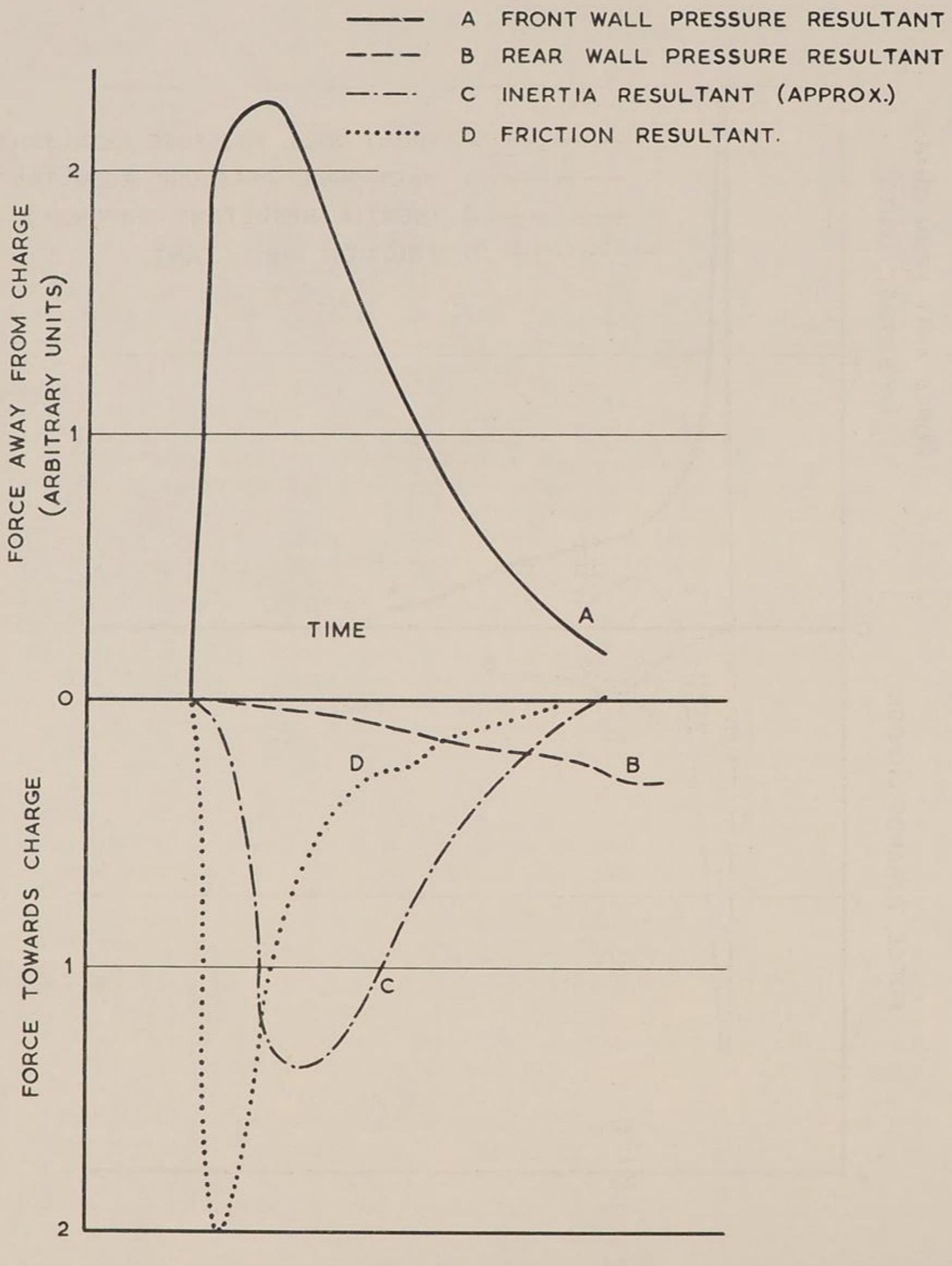
D.N.W.
MAY 1958



TYPICAL FORCES ACTING ON MODEL STRUCTURE
BURIED IN DRY CLAY

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CHAPTER 3 - TUNNELS IN ROCK

3.1. Damage Zones

When a charge is exploded close to an unlined tunnel in rock, the resulting damage can be divided into four distinct zones, as shown in Figure 1.

Zone 1 is characterised by complete collapse of the rock between the tunnel surface nearest to the charge and the surface of the ground. The crater opens into the tunnel.

Zone 2 is characterised by a volume of continuous rock breakage increasing in thickness as the charge position is approached. The breakage is not confined to the area along the tunnel surface nearest the charge, but extends well around the tunnel. The general shape of the damage profile is distinctly inclined to the original axis of the tunnel. The outer limit of Zone 2 is where this profile becomes nearly parallel to the original rock surface. If the tunnel diameter is sufficiently great the mechanism of damage for Zones 1 and 2 can be related to the formation of an inverted crater, the tunnel being considered to be replaced by an infinite free surface. (See Section 3.2)

Zone 3 is characterised by a volume of continuous rock breakage of a relatively uniform thickness confined to the area along the tunnel surface nearest to the charge. The general shape of the damage profile is nearly parallel to the original rock surface. The outer limit of Zone 3 is that point beyond which rock breakage and the damage profile become discontinuous. Whereas in Zones 1 and 2 the displaced rock travels with considerable velocity, Zone 3 is that region where the propagated stress waves are just sufficient to crack the rock, which then falls with a low velocity.

Zone 4 is characterised by irregular and intermittent rock breakage along the tunnel surface on the side nearest the charge, and the damage profile is discontinuous in this zone. The outer limit of Zone 4 is that point beyond which no significant rock breakage occurs. The mechanism of Zone 4 damage is considered to be that the stress waves from the explosion are sufficiently great to cause the fall of any rock previously weakened by the construction of the tunnel. This accounts for the intermittent nature of the damage.

The approximate extent of the various damage zones in rock is shown in Figure 2. The values refer to a surface burst nuclear explosion of 1 kiloton total yield. To obtain damage distances for yields other than 1 kiloton, multiply the tunnel depth and the horizontal distance given in Figure 2 by the cube root of the yield in kilotons.

The shock front is assumed to be spherically symmetrical around the burst point in sound rock. To predict the horizontal distance to a certain zone of damage to tunnels, from underground bursts of the same yield, multiply the distance obtained from scaling Figure 2 by the ratio:

$$\frac{\text{Crater radius for actual weapon yield and burst depth used}}{\text{Crater radius for actual weapon yield, burst at the surface.}}$$

For the appropriate crater radii see Chapter 1.

These data refer to ground burst weapons. The quoted distances increase with depth of burst, attaining values 2.5 times as great for burst depths of 45 $W^{1/3}$ feet.

For weapons exploded in media other than soft rock, the distances should also be multiplied by the factors given in Table 1, derived from Reference (3).

Table 1

Soil Factors for Tunnel Damage

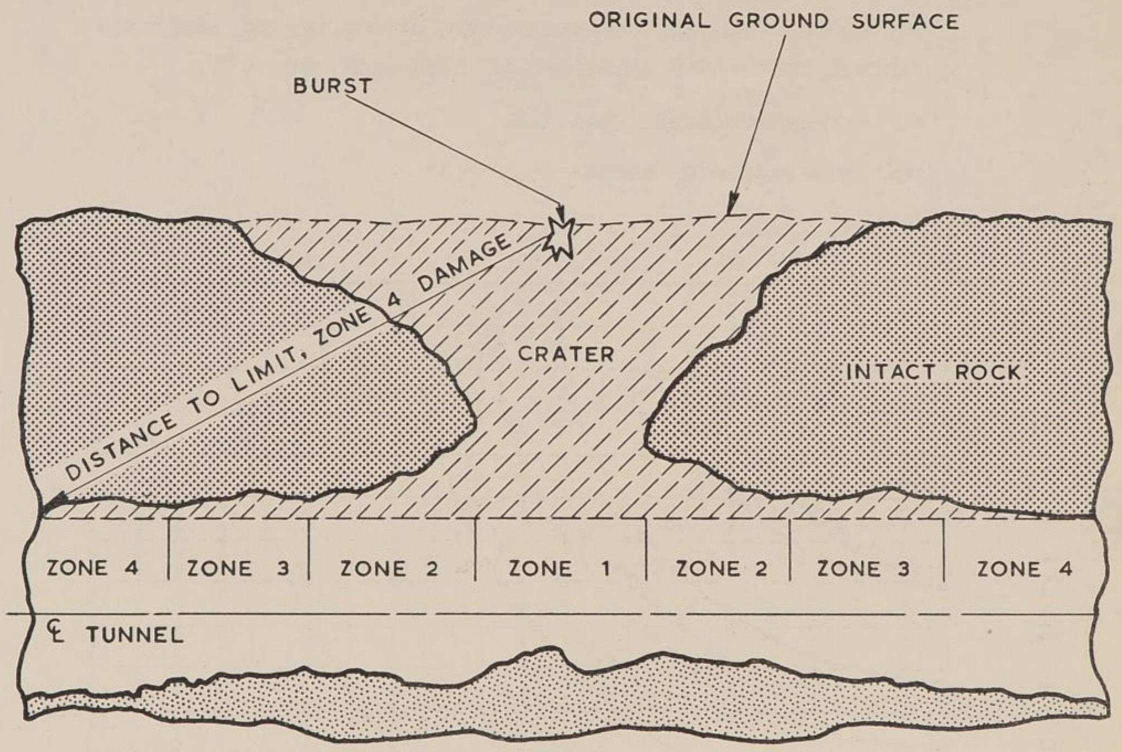
SOIL	FACTOR
Hard rock	0.8
Soft rock	1.0
Hard chalk	1.1
Soft chalk	1.3
Blue clay	1.4
Lime	1.5
Gravel	1.6
Sand	1.8
Made ground	2.1

References

(1) Underground Explosion Test Programme. Final Report, Vol.2. Rock. Engineering Research Associates, April, 1953.

(2) Underground Structures. Tripartite Conference Paper Z9, February, 1954. Ministry of Defence.

(3) Structural Defence - Christopherson. RC.450



ZONES OF DAMAGE TO UNLINED TUNNELS IN SOUND ROCK:–

ZONE 1. CRATER OPENING INTO TUNNEL.

ZONE 2. INCREASING THICKNESS OF SPALLING.

ZONE 3. CONTINUOUS SPALLING OF ABOUT CONSTANT THICKNESS.

ZONE 4. INTERMITTENT LIGHT SPALLING.

DAMAGE ZONES FOR TUNNELS

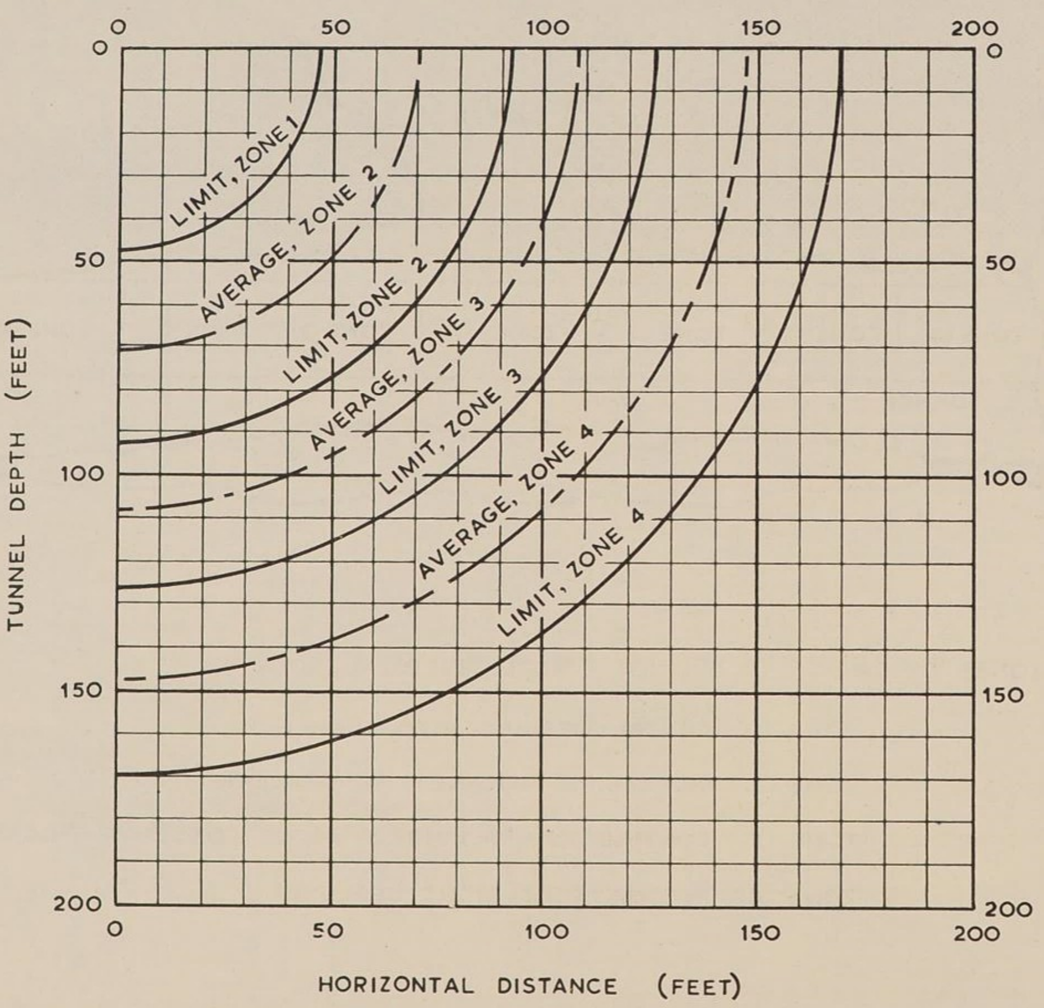
CONFIDENTIAL

CURVES REPRESENT 1 KT CONTACT SURFACE BURST.

TO OBTAIN DAMAGE DISTANCES FOR OTHER YIELDS, MULTIPLY TUNNEL DEPTH AND HORIZONTAL DISTANCE BY $W^{\frac{1}{3}}$.

FOR OTHER SOILS SEE TABLE 1.

FOR UNDERGROUND BURSTS SEE TEXT.



APPROXIMATE ISODAMAGE CONTOURS
FOR UNLINED TUNNELS IN ROCK

CONFIDENTIAL

3.2 Damage Mechanisms

The wavelength of the stress waves near the centre of a nuclear explosion is of the order of 160 $W^{\frac{1}{3}}$ feet. Tunnels whose diameters were more than about six times this wavelength would act as almost perfect reflectors for the stress waves, so that the stress field close to the tunnel would approximate that near an infinite free surface. The stresses at the tunnel walls can be calculated from the laws of reflection of elastic waves, and the tunnel will collapse if these stresses exceed the breaking stress for the rock.

In the more usual case of tunnels whose diameters are several times smaller than the wave-length of the propagated stresses, very little energy is reflected at the tunnel surface and the tunnel is subjected to a quasi-static stress field. The stresses in this case are also calculable, and the same criterion for collapse applies.

3.2.1 Elastic wave reflection

When a plane compressional wave is reflected at normal incidence at an infinite free surface, the reflected wave is a tension pulse. For other angles of incidence transverse waves are generated in addition to the reflected longitudinal tension wave.

Notation:
- i = Angle of incidence
- r = Angle of reflection of the transverse wave
- v_L = Velocity of propagation of the longitudinal wave
- v_T = Velocity of propagation of the transverse wave
- ν = Poisson's ratio
- A_L = Amplitude of incident longitudinal wave
- B_L = Amplitude of reflected longitudinal wave
- B_T = Amplitude of reflected transverse wave.

The angle of reflection of the transverse wave is given by:-

$$\frac{\sin i}{\sin r} = \frac{v_L}{v_T} = \left[\frac{2(1-\nu)}{1-2\nu}\right]^{\frac{1}{2}} \qquad 3.2.1$$

The angle of reflection of the longitudinal wave is the same as the angle of incidence.

The amplitude of the reflected longitudinal wave, as a fraction of the incident wave, is given by:-

$$\frac{B_L}{A_L} = \frac{\sin 2i.\sin 2r - (v_L/v_T)^2 \cos^2 2r}{\sin 2i.\sin 2r + (v_L/v_T)^2 \cos^2 2r} \qquad 3.2.2$$

The amplitude of the reflected transverse wave as a fraction of the incident wave is given by:-

$$\frac{B_T}{A_L} = \frac{2(v_L/v_T)\sin 2i.\sin 2r}{\sin 2i.\sin 2r + (v_L/v_T)^2 \cos^2 2r} \qquad 3.2.3$$

These relations are shown graphically in Figure 1. If the incident stress is known, they suffice for the stresses at the tunnel wall to be calculated, and the extent of damage thereby predicted.

/Values

Values of the incident stress are given as a function of distance, soil type and yield, in Chapter 2 of M.E.A.W. (Reference (3)).

3.2.2 Static stress fields

When a plane wave of long wavelength is incident at a tunnel, the stresses can be approximated to those in a steady compressional field. In these circumstances the ratio of normal to transverse stress (away from the tunnel) is given by:-

$$\frac{\sigma_t}{\sigma_n} = \frac{\nu}{1 - \nu} \qquad 3.2.4$$

where σ_t is the transverse compressional stress (in the plane of the wave)

σ_n is the normal stress (in the direction of propagation)

ν is Poisson's Ratio.

The stress distribution around a tunnel remote from the surface of the ground is shown for this case in Figure 2, where Poisson's ratio has been assumed to be 0.25.

The maximum tangential stress is 2.7 times the applied incident stress, and occurs at the face of the tunnel at 90° to the direction of propagation. It follows that if the incident stress were to exceed 1/2.7 times the compressive strength of the material, scabbing would occur.

The picture presented above neglects various complicating factors. For instance, in practice the incident wave is not plane, so that equation 3.2.4 does not hold precisely. The effect is to cause tension cracks at the point closest to the weapon.

The presence of the free surface of the ground modifies the stress field to an extent which is important if the tunnel is close to the surface. This effect is analysed in Reference (2), where it is shown that the effect of the free surface on stress distribution is negligible providing that the depth of the centre of the tunnel is greater than 1.5 tunnel radii. For tunnels whose centre is shallower than 1.2 radii, the stresses increase with great rapidity as the hole approaches the surface of the ground.

The static stress due to the weight of rock above the tunnel must also be taken into account in any damage prediction. For a tunnel situated at depth d feet below the surface of rock, whose density is ρ pounds per cubic foot, the rock weight increases the static field by $\rho d/144$ lb./sq. in. This also applies to the tangential stress σ_n.

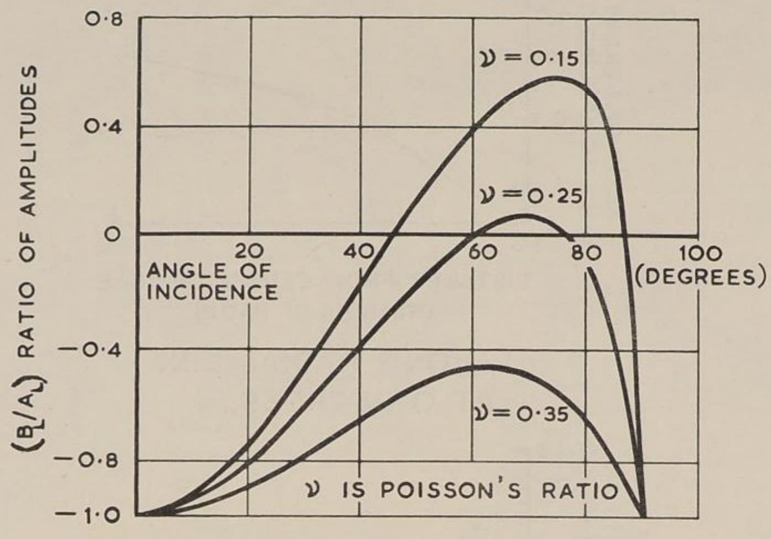
The position of the water table is also of significance in this type of calculation, but no data are available at present.

Reference

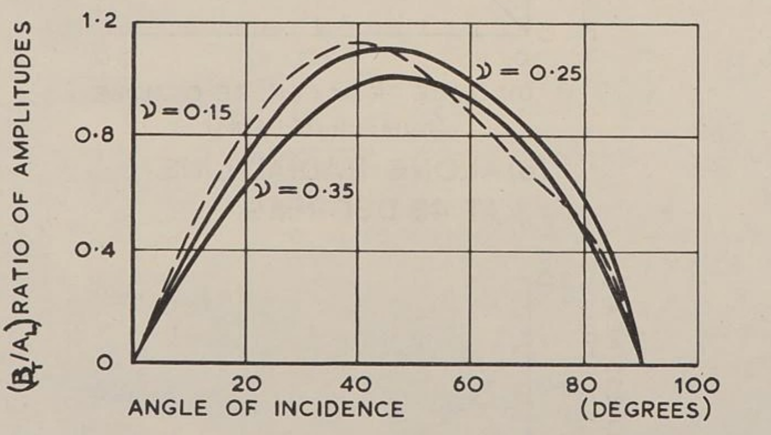
(1) Underground Test Programme, Final Report, Vol. 2. Rock Engineering Research Associates.

(2) Stress Distribution Around a Tunnel. R.D. Mindlin, Proc. A.S.C.E. Vol. 65, pp 612-642 (1939).

(3) Manual on The Effects of Atomic Weapons, Chapter 2. A.W.R.E. (Secret/Atomic/U.K. Eyes Only).



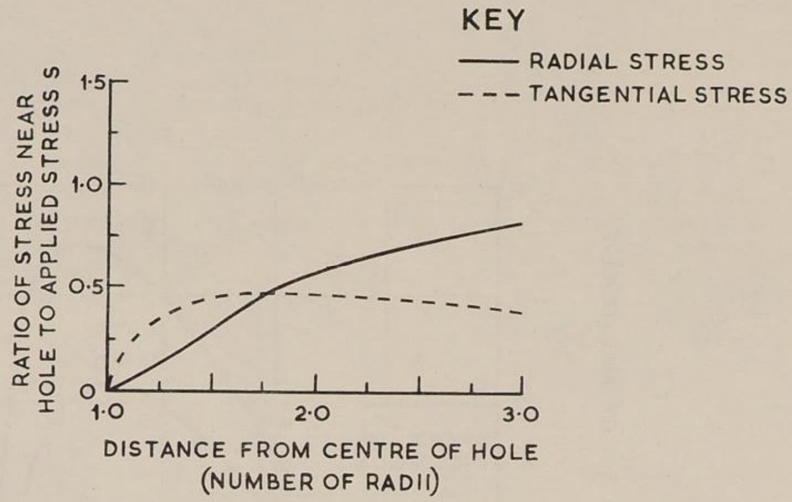
(A) REFLECTED LONGITUDINAL WAVE



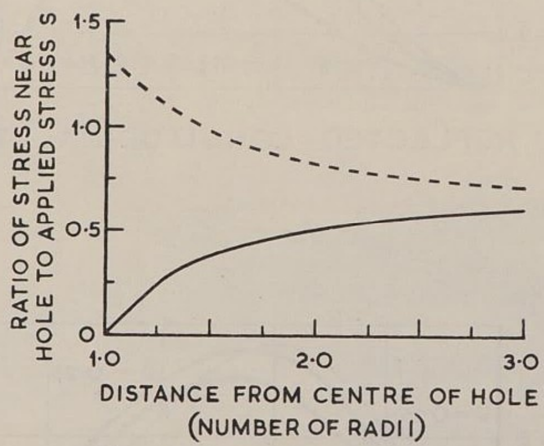
(B) REFLECTED TRANSVERSE WAVE

AMPLITUDES OF REFLECTED LONGITUDINAL AND TRANSVERSE WAVES RELATIVE TO AMPLITUDE OF A PLANE LONGITUDINAL WAVE INCIDENT ON A PLANE FREE SURFACE

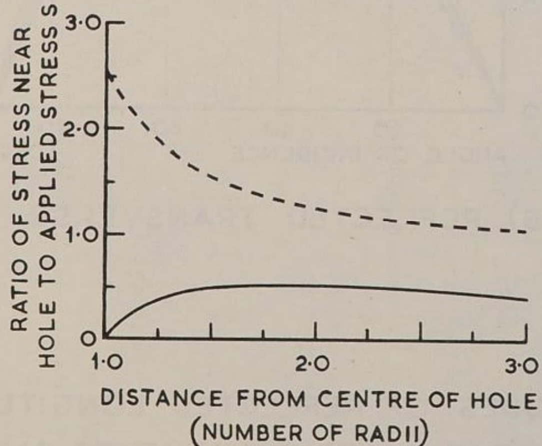
UNCLASSIFIED



(a) ALONG RADIAL LINE
AT 0 DEGREES



(b) ALONG RADIAL LINE
AT 45 DEGREES



(c) ALONG RADIAL LINE
AT 90 DEGREES

STATIC STRESSES AROUND A CIRCULAR HOLE IN AN INFINITE PLATE FOR A TWO-DIMENSIONAL APPLIED STRESS FIELD

UNCLASSIFIED

3.3. Fly Velocities

In Zones 1 and 2, as defined in Section 3.1, pieces of rock are projected with considerable velocity. In the case of H.E. charges, the velocity of sandstone fragments in a tunnel has been measured for the point closest to the explosion, and allowing for the reduced efficiency of nuclear explosions, the fly velocity U approximates

$$U = 4.10^4 \; (L/W^{\frac{1}{3}})^{-1.4} \qquad 3.3.1.$$

where U = Fly velocity (feet per second)

L = Distance of tunnel from weapon (feet)

W = Weapon yield (kilotons)

As crater or cavity radii are of the order of $50W^{\frac{1}{3}}$–$200W^{\frac{1}{3}}$ feet, the likely magnitude of U in the various zones can be seen from Table I.

Table I - Fly Velocities for Sandstone
(From Equation 3.3.1.)

$L/W^{\frac{1}{3}}$	U
50	180
100	63
200	24
400	9
1000	$2\frac{1}{2}$

References

(1) Underground Explosion Test Programme. Final Report, Vol. 2, Rock. Engineering Research Associates Inc., 1953.

3.4. Protection Against Damage

According to current American information, it is possible to protect against damage in Zones 3 and 4 by inserting an appropriate tunnel lining. This lining should be sufficiently strong to hold back any loose material, and should be supported from the main rock surface by a low impedance layer. This ensures that the lining is protected from the stress waves of the explosion, so that any scabbing takes place at the surface of the rock itself. The fly velocities experienced in Zones 1 and 2 are too great to make the design of a protective lining practicable.

References

(1) Underground Explosion Test Programme. Final Report, Vol. 2 - Rock. Engineering Research Associates Inc., 1953.

CHAPTER 4 - SURFACE STRUCTURES

4.1. Introduction

The ground motion resulting from an atomic explosion is described in detail in Chapter 2 of M.E.A.W.. Briefly, the intense pressure of the explosion causes stress waves to be propagated through the ground, and the resulting ground motion takes the form of a damped oscillation. The fundamental frequency of this oscillation depends upon the size of the weapon and the nature of the ground. It may be expected to lie between 0.1 and 10 cycles per second. The corresponding wavelengths vary between 20,000 and 500 feet. The amplitude of the motion as a function of distance is given in M.E.A.W. for various burst conditions.

An additional motion is induced in the ground when the air blast passes over it. This takes the form of a discontinuous change in the ground velocity, which is approximately proportional to the change in air pressure.

The ground motion causes stresses to be set up in a surface structure in two different ways. Firstly, inertial forces are set up in the structure as the base moves with the surrounding ground, and secondly, the differential displacements between the ends of a building may cause the building to collapse. Insufficient evidence is at present available to enable a complete analysis to be made of the failure of typical structures under the action of a given ground motion. In particular, more information is needed about the internal resistance of structures when they are stressed beyond their elastic limit. Currently available information is summarised in Section 4.5. It may however be noted that damage to surface structures will, in general, be due to air blast rather than to ground shock, unless the weapon bursts at a depth greater than about 35 $W^{\frac{1}{3}}$ feet.

Another possible approach is to use the evidence that has been accumulated as a result of the study of earthquakes. The energy released in a "damaging" earthquake is comparable with that released in a nuclear explosion, and it is reasonable to suppose that the forces acting on structures are not very different in the two cases. (Reference (2), page 111.). By relating the degree of damage to structures caused by a shallow earthquake to the amplitude of the earthquake motion, it is possible to assess the likely damage by the ground motion due to an atomic weapon. This method is described in Section 4.2.

Another method is to use certain ad hoc rules for assessing the damage by a given ground motion to a given structure. These rules are presented in Section 4.3.

It has already been mentioned that, for most surface structures, airblast rather than ground shock is the significant damaging agent in the case of near surface bursts. This obviously does not apply to low flat structures, such as aircraft runways. Bridges on piers may represent an intermediate case, but few data are available.

References

(1) Manual on the Effects of Atomic Weapons. Chapter 2. A.W.R.E. (Secret/Atomic/U.K. Eyes Only)

(2) The Effects of Atomic Weapons. U.S. Government Printing Office, 1950

(3) Considerations Leading to a Programme for the Study of Ground Shock and the Necessary Instrumentation. A.W.R.E. Report O-19/1954. (Confidential)

References (Contd.)

(4) Symposium on Earthquake and Blast Effects on Structures, Los Angeles, June, 1952. Symposium sponsored by Earthquake Engineering Research Institute and University of California.

(5) Earthquake Damage and Earthquake Insurance, Freeman, McGraw-Hill, 1932.

(6) Underground Structures. Ministry of Defence Paper, Z9, Tripartite Conference, 1954.

4.2. Results of Earthquake Studies

For many years it has been the custom to assess the strength of an earthquake motion at a given point by the degree of damage there. Many arbitrary Intensity Scales have been devised, one of the most widely used being the modified Mercalli Intensity Scale of 1931, (Reference (1)). A summary is given in Table 1.

Gutenberg and Richter (Reference (2)) have related the Intensity of the earthquake to the maximum acceleration in the wave. The relationship found was:

$$\log_{10} a = \frac{I_M}{3} - \frac{7}{2} \qquad 4.2.1$$

where a = peak acceleration in 'g' units

I_M = Modified Mercalli Intensity.

Since an earthquake and a nuclear explosion can consist of the sudden release of a comparable amount of energy, it is reasonable to assume that the resulting effects can be related, at any rate approximately. If so, it should be possible to obtain a general assessment of the degree of damage from a given ground shock by determining the modified Mercalli Intensity by means of equation 4.2.1, and then looking up the corresponding damage in Table 1. For convenience, the accelerations in 'g' units are also indicated.

An alternative scale sometimes used is Richter's Magnitude Scale. This is based on the logarithm of the amplitude of motion, the Magnitude (M) of the earthquake being related to its Energy (E), relative to a standard or zero magnitude earthquake of energy $E_0 = 2 \times 10^{11}$ ergs. The relationship is:

$$M = \frac{1}{1.8} \log (E/E_o)$$

The smallest earthquakes felt are of magnitude 1.5, while those of magnitude 4.5 will cause slight damage near the epicentre. Those of magnitude 6 are destructive over a limited area, and magnitude 7.5 is the lower limit of major earthquakes. The results in Table 2 give an approximate relationship between the energy and the type of earthquake. These energies may be compared with the total energy release of an atomic bomb of 4×10^{16} ergs per kiloton, of which it will be recalled only a proportion appears as earth shock.

Table 1 - Modified Mercalli Intensity of 1931 (Abridged)

Intensity	Accelerarion	Effects
I	0.0006g	Not felt except by a very few under especially favourable circumstances.
II	0.0014g	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	0.003g	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognise it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	0.006g	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	0.014g	Felt by nearly everyone; many awakened. Some dishes, windows and so forth broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	0.03g	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	0.06g	Everybody runs outdoors. Damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures, considerable in poorly-built or badly designed strctures; some chimneys broken. Noticed by persons driving motor cars.
VIII	0.14g	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly-built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned; Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	0.3g	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

Table 1 (Contd.)

Intensity	Acceleration	Effects
X	0.6g	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	1.4g	Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe pines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	3g	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Table 2

	Energy Range ergs	Magnitude of mean
Great earthquakes	10^{26}	8.
Major earthquakes	$10^{24} - 10^{26}$	7.5
Destructive earthquakes	$10^{22} - 10^{24}$	6.5
Damaging earthquakes	$10^{20} - 10^{22}$	5.5
Minor strong earthquakes	$10^{18} - 10^{20}$	4.5
Generally felt small earthquakes	$10^{16} - 10^{18}$	3.0

For further discussion see Reference (3)

The earthquake damage scale given in Table 3 was used by the National Research Council in Reference (4). The accelerations given in the Table are those in a horizontal direction.

Table 3 - Earthquake Damage Scale

Grade A - Very violent (greater than 0.4 gravity).

Grade B - Violent (0.3-0.12 gravity).
Fissuring of asphalt; destruction of foundation walls and under-pinnings of structures; the breaking of sewers and water mains; displacement of street car tracks.

Grade C - Very strong (0.12-0.08 gravity)
Brick walls or masonry badly cracked with occasional collapse; frame buildings lurched or listed on fair or weak underpinning; general destruction of chimneys and masonry, cement or brick veneers; considerable cracking or crushing of foundation walls.

Table 3 (Contd.)

Grade D - Strong (0.08-0.02 gravity)
General but not universal fall of chimneys; cracks in masonry and brick walls; cracks in foundation walls; a few isolated cases of lurching or listing of frame buildings built up on weak underpinning.

Grade E - Weak (less than 0.02 gravity)
Occasional fall of chimneys and damage to plaster, partitions, plumbing, etc.

References

(1) Wood and Neumann "Modified Mercalli Intensity Scale, 1931" Bulletin of the Seismological Society of America, Vol. 21, pages 277-283, 1931.

(2) Gutenberg and Richter "Earthquake Magnitude, Intensity, Energy and Acceleration". Bulletin of the Seismological Society of America, Vol. 32, pages 163-191, 1942.

(3) Introduction to Theory of Seismology, K. E. Bullen, Cambridge University Press.

(4) Physics of the Earth, Part VI, Seismology. Bulletin of the National Research Council No. 90, 1933.

4.3. Ad hoc Rules for Determining Structural Damage

Various authors have given rules which relate structural damage to one or other of the parameters describing the motion, such as the maximum acceleration (References (1) and (2)), the maximum displacement (Reference (3)), and the "energy ratio", defined as $4\pi^2$ times the product of the maximum acceleration and displacement (Reference (4)). Theoretical considerations (Reference (5)) suggest that the factor most clearly related to structural damage is velocity, and this is a function of the "energy ratio" for a given wave shape. For a sinusoidal wave shape, the maximum velocity is simply equal to $1/2\pi$ times the square root of the "energy ratio" .

American workers have estimated the "energy ratio" required to damage various types of structure (Reference (6)). The majority of the figures were obtained by taking a "concensus of qualified persons", and it is difficult to assess their reliability. Table I is based on the American report, but the values of the "energy ratio" have, for convenience, been converted to velocities, assuming simusoidal wave shapes.

It will be appreciated that the results quoted only apply to average cases, and that the rules are too simple to predict the behaviour of a particular structure with any degree of certainty.

Table I

Item	Damage	Velocity (ft./sec.)	Remarks
Bridges	Severe	1.6	Bridge collapses
	Moderate	0.85	Bridge displaced
Airfield Runway Landing mat (steel)	Severe	1.1	Mat twisted and buckled
Airfield Runway* Landing strip (concrete)	Severe	2.0	Concrete cracked and displaced
	Moderate	1.5	Concrete will crack
	Light	1.0	Concrete slightly cracked
General Machinery (bolted down)	Severe	0.8	Gears and functional parts destroyed
	Moderate	0.6	Auxiliary equipment destroyed
	Light	0.5	Destroys alignment
Railway locomotives and rolling stock	Severe	1.1	Pushed over and twisted Probable fires
	Moderate	0.7	Derailment
Brick walls (12-18in.)	Severe	0.6	Collapse
	Moderate	0.5	Partial collapse and cracking
	Light	0.4	Cracking
Houses - brick	Severe	0.6	Collapse
	Moderate	0.5	Distortion and cracks
	Light	0.4	Plaster and window damage
Houses - wooden frame	Severe	0.8	Collapse
	Moderate	0.6	Distortion and cracks
	Light	0.45	Plaster and window damage
Multistory brick building	Severe	0.6	Collapse
	Moderate	0.5	Structural damage
	Light	0.4	Plaster and window damage
Reinforced concrete building	Severe	0.85	Collapse
	Moderate	0.7	Structural damage
	Light	0.6	Plaster and window damage
Steel, heavy frame building	Severe	0.7	Mass distortion
	Moderate	0.5	Structural damage
	Light	0.45	Plaster and window damage
Steel, light frame building	Severe	0.6	Mass distortion
	Moderate	0.5	Structural damage
	Light	0.4	Plaster and window damage
Underground pipes*	Severe	0.85	Pipes broken
Dams (cement)*	Severe	1.0	Cracked and displaced
Dams (earth)*	Severe	1.6	Cracked and displaced
Submarine pens*	Severe	1.6	Cracked and displaced
Railway lines*	Severe	1.6	Rails bent

*Note: There is experimental evidence to support this figure with these items.

References

(1) Gutenberg and Richter. "Earthquake Magnitude, Intensity, Energy and Acceleration". Bulletin of the Seismological Society of America, Vol. 32, No. 3, July, 1942, pp 163-191.

(2) Thoenen & Windes. U.S. Bureau of Mines Bulletin 442, 1942.

(3) Morris & Westwater. "Damage to Structures by Ground Vibrations due to Blasting". Mine & Quarry Engineering, April, 1953.

(4) Crandell. "Ground Vibration due to Blasting and its Effect Upon Structures".

(5) Considerations leading to a Programme for the Study of Ground Shock and the necessary Instrumentation. A.W.R.E. Report No. O-19/54. (Confidential)

(6) United States A.F.S.W.P. Paper 22 for 1954 Tripartite Conference. The Capabilities of Atomic Weapons. Ministry of Defence.

4.4. Calculation of the Motion of a Structure Under the Action of the Inertial Forces Generated when its Base is Accelerated

Experiments show that when a structure is moved under the action of ground shock forces, the base of the structure follows the motion of the ground - Reference (1) - and the vertical forces which are then set up in it may be sufficient to cause damage. The detailed analysis of the motion of any real structure is exceedingly complex, but a sufficient approximation can often be obtained by treating the structure as a system with one degree of freedom.

If x represents the displacement of the centre of gravity of the structure relative to the base, and R_D represents the resistance per unit mass of the structure against its deflection, when the ground acceleration is a(t), the equation of motion of the structure is:

$$\ddot{x} + R_D(x,t) = -a(t) \qquad 4.4.1.$$

In general, R_D is a function of the deflection x at time t, as well as of the history of the deflections at all previous times. The full solution of this equation requires more knowledge of the plastic deformation of structures than is in general available. It is however, possible to make reasonable assumptions about the form of R_D, and then obtain a solution by numerical or graphical phase-plane methods, Reference (2), or by direct numerical integration, Reference (3). Such methods are outlined in Chapter 6 of Part III of this Manual.

Another method commonly used is to replace the resistance function by a linear restoring force $\omega_0^2 x$, and a viscous damping $2n\omega_0\dot{x}$ where ω_0 and n are constants. The equation of motion now becomes:

$$\ddot{x} + 2n\omega_0\dot{x} + \omega_0^2 x = -a(t) \qquad 4.4.2.$$

The disadvantage of this method is that the concept of damping is somewhat artificial, and in fact the value of n increases with the amplitude of motion (Reference (4)). A general solution of equation 4.4.2. is:

$$x = -\frac{1}{\omega_0\sqrt{1-n^2}} \int_0^t a(t) \,.\, e^{-n\omega_0(t-\tau)} \,.\, \sin\left[\omega_0\sqrt{1-n^2}\,(t-\tau)\right] .d\tau \qquad 4.4.3.$$

The numerical evaluation of this integral is very laborious but it is relatively easy to build an analogue computor to solve equation 4.4.2 directly - Reference (5).

One experiment (Reference (6)) has been conducted in which the actual motion of the centre of gravity of a steel-framed building was measured during a strong ground shock and excellent agreement was obtained with the motion predicted by the use of an analogue computor.

References

(1) K. B. Vaile - "Final Report on The Surface Structure Programme. Underground Tests at Dugway". Stanford Research Institute, Contract DA-04-167, eng-379, 1952.

(2) Jacobsen - "Dynamic Behaviour of Simplified Structures up to the Point of Collapse". Symposium on Earthquake and Blast Effects on Structures. Engineering Research Institute, California, 1952.

(3) Newmark - "Computation of Dynamic Structural Response in the Range Approaching Failure" . Symposium on Earthquake and Blast Effects on Structures. Engineering Research Institute, California, 1952.

(4) Alford and Housner - "A Dynamic Test of a Four-Storey Reinforced Concrete Building". Bulletin of the Seismological Society of America. Volume 43, pp 7-16, 1953.

(5) Housner and McCann - "The Analysis of Strong Motion Earthquake Records with the Electric Analog Computor". Bulletin of the Seismological Society of America, Volume 39, pp 47-56, 1949.

(6) Hudson, Alford and Housner - "Measured Response of a Strucutre to an Explosive-Generated Ground Shock". Bulletin of the Seismological Society of America, Volume 44, pp 513-527, July, 1954.

(7) Newmark, N.M. "An Engineering Approach to Blast Resistant Design". American Society of Civil Engineers. Transactions Vol. 121 (1956) Paper No. 2786. (Reprinted as University of Illinois Bulletin, Vol. 53, No. 73, June, 1956. Engineering Experiment Station Reprint Series No. 56).

4.5. The Resistance of Structures

As stated in Section 4.4, the inertial forces acting on a structure and its internal resistance, both depend in a complex manner on the motion of its base and on the previous plastic deformations which the structure may have undergone. However, it is possible to define approximately the resistance of a structure by the equivalent damping and restoring force method. The behaviour of the structure is then defined by the constants n and ω_o of equation 4.4.2.

The damping constant n varies widely from building to building, measured values having been found between n=0.001 and n = 0.5. For a structure vibrated well into its plastic region, the value of n is expected to lie between 0.1 and 0.5.

An extensive survey of the fundamental frequencies of buildings has been undertaken by the United States Coast and Geodetic Survey - Reference (1). They find that although factors such as the shape of the building, type of construction, and the type of ground on which the structure is built, all affect the fundamental period, it is possible to define ω_o to a fair degree of approximation by the equation:

$$\omega_o = 120\sqrt{b/h} \qquad 4.5.1.$$

where ω_o = 2π times the fundamental frequency (sec $^{-1}$)

b = the breadth of the building (feet)

h = the height of the building (feet)

When these values of n and ω_o are fitted into equation 4.4.2. that equation suffices to define the motion of a building at any time. If the amplitude of the induced vibration exceeds a certain value, the structure will collapse. Little information is available on this critical value. In a single experiment a brick farmhouse was demolished by A.W.R.E. - Reference (2) - and it was found that the structure collapsed under a steady pull when the centre of gravity had been displaced laterally through a distance of about 10 percent of the height of the building.

It should be emphasized that this is an isolated example, and that the house was demolished by a single slow pull rather than by transient oscillatory forces.

References

(1) F. P. Ulrich and D. S. Carder - "Vibrations of Structures" Symposium on Earthquake and Blast Effects on Structures". Los Angeles, June, 1952.

(2) Static Demolition of a Farmhouse. A.W.R.E. Report H3/51 (Restricted)

4.6. Differential Displacement Between the Ends of a Surface Structure

The wavelength of the propagated ground shock from a nuclear explosion depends on the size and position of the burst and on the nature of the ground, but will be between 500 and 20,000 feet. This is greater than the length of most structures. For such cases the differential displacement between the ends of a structure is given, as in Reference (1) by:

$$\Delta = lu/v_L \qquad 4.6.1$$

where Δ = differential displacement between the ends of the building (feet)

l = length of the building (feet)

u = maximum value of the horizontal component of the surface particle velocity

v_L = velocity of propagation of the particular seismic wave.

When the length of the structure is greater than the wavelength of the ground shock, the differential motion across the building follows the motion of the ground. The differential displacement between two points of the structure half a wavelength apart is now:

$$\Delta = 2A_G \qquad 4.6.2.$$

where A_G = amplitude of the ground wave.

No information is available on the resistance of a structure to differential displacements of its base, nor on the consequent damage.

References

(1) Considerations leading to a programme for the study of ground shock and the necessary instrumentation. A.W.R.E. Report No. O-19/54 (Confidential)

CHAPTER 5 - DEBRIS FROM SURFACE BURSTS

5.1. Relation to Other Damage

American workers have found experimentally that the region of severe damage by air blast extends well beyond the zone in which missiles of rock, etc., thrown out by the explosion, are of damaging importance. For example, for a nominal weapon, assuming missiles such as would be produced from a concrete wunway, serious damage to buildings on account of air blast would be expected out to 2,200 feet, but on account of missiles, only out to 1,100 feet. Similarly, air blast damage to aircraft would occur out to 6,000 feet, but missile damage only out to 3,000 feet.

For further details of damage by flying fragments and debris distribution from bursts, see Chapter 7 of Part III of this Manual.

References

(1) Cratering and Earth Shock, Paper Z8. Tripartite Conference, 1954.

(2) Distribution and Density of Missiles from Nuclear Explosions. Operation "Teapot", 1955. Project 33.4, C.E.T.G. Reference ITR-1168. (Confidential/Restricted Data)

(3) The Effects of a Nuclear Explosion on Records and Record Storage Equipment. Operation "Teapot", 1955. Project 35.5, C.E.T.G. Reference ITR-1191 (Unclassified)

CHAPTER 6

The Vulnerability of Underground Installations and other Protective Construction to the Effects of Nuclear Weapons

Editor's Note

This chapter was originally prepared as a paper for the Nuclear Weapons Lethality Committee, and at the Committee's request is now published as a chapter of the manual.

A list of reports relating to the vulnerability of protective construction has been compiled and is presented at the end of the chapter. Many of these reports are of U.S. origin and some are not yet available in the U.K. A comprehensive review of this information has therefore not been possible. However, with the possible exception of earth shock, the response of protective installations to nuclear effects is sufficiently predictable to permit their design and construetionnto specific levels of protection with reasonable confidence.

It was with this object that the U.S. publication "Protective Construction Review Guide" was written in late 1958, and it represents the U.S. philosophy on the subject at that date. This paper is substantially a summary of the "Review Guide", with the object of highlighting the structural requirements, design features, and approximate costs of protective installations, particularly underground construction required to withstand severe stresses.

D1/57 November, 1960

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Table 1 - Cost Data

Bibliography

A. General Design Studies

B. General Target Response Information

C. Trials Reports

D. Special Studies of Aircraft Shelters

E. Special Studies of Rocket Launchers

F. AWRE Ground Shock Reports.

Figures 1-11

The Vulnerability of Underground Installations and other Protective Construction to the Effects of Nuclear Weapons

1. Introduction

In designing an installation to resist nuclear weapons the following weapon effects must be considered:-

(i) the immediate nuclear and thermal radiation:

(ii) the shock transmitted through the ground:

(iii) the blast forces:

(iv) the radiation from fallout, and induced radiation resulting from the immediate effects of neutrons on materials.

The level of radiation intensity and of shock and blast which an installation must resist depends on a number of factors over which the designer has no control. These include: the size of the weapon and the distance from the target at which it is detonated, or the overpressure level which is produced at the installation by the weapon considered; the number of weapons which are successfully detonated in the vicinity of the installation; and the overall pattern of attack, which may bring residual radiation from fallout to a target which is not near any nuclear burst. To deal with these factors the designer may select the ground environment, the structural mass and strength of the elements of the installation, and the arrangement and multiplicity or duplication of those elements in a pattern which will give the desired probability of survival.

This leads to tentative conclusions on design parameters which may have to be modified in the light of operational conditions, and survival criteria for personnel and materials. A selection must then be finally made of the structural type and design parameters, which can be stated generally in terms of the overpressure level and radiation intensity levels, for both immediate and residual radiation, and the level of earth shock, for which each element of the facility must be designed.

2. Structural Design

As mentioned above, in order to obtain design parameters for a structure, conditions must be chosen which the structure must resist to give the desired probability of survival. For example, given the yield and C.E.P. of the weapon against which protection is being designed, and having chosen an appropriate probability of survival consistent with the importance of the facility, a radius of vulnerability (Rv) may be obtained from Figure 1. Then from Figure 2 using this Rv and the chosen yield, a value of the maximum overpressure for the selected survival probability may be found. In a similar manner Rv may be related to initial radiation dose. The necessary charts for this are not given here but are available in References 25 and 26.

It is then necessary to determine the structural resistance required, taking into account the span or other controlling dimensions of the structure, the structural materials, and the range of behaviour of the structure for which the design is being prepared.

Appendix 5A of Reference 1, give a series of design charts which may be used to determine the approximate size required for various structural elements such as slabs, beams, arches, domes, columns, footings or frames for any level of overpressure.

In order to determine the required size of elements it is necessary to use the dynamic strengths of the materials, for example the dynamic compressive strength of concrete and the dynamic yield strength of steel. The magnitude of these dynamic strengths, taking into account increase in strength due to the rapid rate of loading, may be found in Appendix 5B of Reference 1.

The requirements for nuclear radiation protection must also be assessed from knowledge of the initial radiation dose (unshielded) and the permissible exposure level inside the installation. For example approximately 100 inches of soil, or about 70 inches of concrete will reduce an initial gamma radiation level of 1,000,000 r to a level of 100 r (possibly an acceptable operational dose). For details of gamma-ray shielding References 25 and 26 should be consulted. Similar neutron attenuation data are not given in these two references, but Figure 3 provides some information on this subject.

Nuclear radiation effects on electronic equipment, and the effects of electro-magnetic flash must also be considered, and suitable protection provided. Some information on this subject is given in References 27, 28, 29 and 30.

Thermal radiation intensity is unlikely to be a predominant factor for structures already designed to withstand severe blast overpressure and provide adequate nuclear radiation shielding. The outside surface of the structure will however suffer severe thermal exposure. For example, at 7,000 ft. from 20 M.T. (equivalent to an overpressure of 200 p.s.i.) the thermal radiation dose is about 4,000 Cal/cm^2.

3. Structural Details

3.1. Concrete Construction. Reinforced concrete is an excellent material for blast-resistant construction, but strict attention must be paid to details in order to assure continuity, ductility and resistance to loads in either direction. In no case should the amount of reinforcing used on any face of a beam or slab exceed 2% of the cross-section area of the element, in order to avoid brittle behaviour.

3.2. Steel Construction. Steel also can be used very economically for certain types of blast-resistant construction. Arch or circular sections for underground construction, steel beams for composite construction, high strength columns, and steel doors for personnel or equipment entrances are elements which may be more economically constructed of steel than of reinforced concrete.

Ductility, continuity and development of full plastic strengths at joints are also recommended for steel construction. Steel members designed for maximum plastic resistance should be able to experience large deflections without reduction in load capacity. Generally such members will be stockier than in conventional design. Recommendations of proportions which would minimise or avoid buckling problems are given in Appendix 5B of Reference 1.

3.3. Protective Doors. The intended function of a protective installation may be achieved or lost according to the attention that is given to the doors. Doors - especially large doors - represent a major structural-mechanical design problem, and door requirements may often influence the type or proportion of the main structure. Careful study of this problem is further necessitated by the fact that the total cost of a large door, including its mechanical and electrical components can represent a significant fraction of the total cost of the protective installation.

3.3.1. Types of Doors. In general doors may be classed in accordance with their attitude: either horizontal, vertical or inclined; and with respect to their method of opening: sliding, rolling, hinged on one side, or opening from hinges on both sides with a join down the centre. A third method of classification involves the configuration: whether the door is flush with a surface, or in recess where under certain conditions advantage may be taken of the containing element in supporting the door when it is subjected to blast forces. The advantages and disadvantages in each type of configuration, method of opening, or attitude are discussed in detail in Section 5.2.3.1. of Reference 1.

3.3.2. Functional Requirements. These may be listed as follows:-

(a) Is more than one opening required and can alternate openings be oriented to minimise the probability of full weapons effects at all locations?

(b) Is the opening at the surface, or inside a tunnel or other shielded location?

(c) How frequently must the door operate.

(d) What is the maximum time available for door operation under attack conditions?

(e) Is the door required to survive only one attack?

(f) Can the orientation of the door (i.e., horizontal, vertical or inclined) be selected to minimise door loading or has it a functional requirement?

(g) Are the human and material contents of the installation to be protected against all attack effects (blast, heat, nuclear radiation, chemical and biological contamination).

3.3.3. Important Door Characteristics

(a) Strength and Stiffness will depend on the degree of deformation which can be tolerated, and this in turn is influenced by the effect of distortion on subsequent operation, and on the effectiveness of joint seals.

(b) Weight The thickness may be governed by required resistance to radiation effects, in which case weight may not be appreciably reduced by skilful design. When thickness is determined by blast loading however, the weight may vary widely with the door form (dome, slab etc.), materials (steel, concrete, or combination), and internal structure (solid, cored, sandwich). The size and cost of the mechanical components of large doors may be very sensitive to the weight of the door structure.

(c) Shape of exposed surface. In many cases the best solution is a flat slab of concrete or steel, but domed surfaces may make more effective use of material. In the dome type however, the inherent strength advantage may be lost through more severe loading associated with reflection

and drag effects on the dome surface, compared with a flat slab. This difference is more pronounced when the slab type door is recessed to make its outer surface flush with the outer surface of the main structure.

(d) Protection of door mechanism. Unless the door is located well inside a tunnel or other shielding, the design should aim to place all mechanism within the protected space. The operating mechanism should also be designed so that it is isolated from the blast forces and motions transmitted by the door or main structure when the door is in the closed position. i.e. support for the closed door structure should be independent of the trunnions, rollers, struts, and other elements of door mechanism.

(e) Power source for door operation. Large doors require very large power expenditure for short periods of time. For day-to-day operation this power can be drawn from a central source exterior to the installation. In such cases a parallel standby power source should always be provided inside the protected space. Hydraulic/pneumatic power systems, which have the advantage of requiring relatively small electric power input to a pressure accumulator, are suitable for this purpose.

(f) Warning and Triggering Device. It is essential that remote warning devices and circuits be provided to initiate door closure, and that these provisions be matched with the door closure time. Consideration should also be given to "fail-safe" circuitry which will initiate door closure in the event of failure of device or circuits.

4. Tunnels and Silos

Long shafts, either horizontal or vertical, present particular problems in design. Such shafts are encountered in tunnels connecting the various structures in a complex, or in vertical shafts housing various kinds of equipment or providing access to structures. The loadings on shafts this kind are much affected by the method of construction and by the properties of the soil. General recommendations for the design loadings which might be used in various conditions likely to be found in practice are given in Reference 1, together with appropriate design procedures and charts.

The construction of underground rocket launching sites has been the subject of special studies, and some relevant reports are listed in Section E of the bibliography.

5. Earth Shock and Shock Mounting

5.1. Earth Shock. The earth shock caused by a nuclear weapon consists of two related parts: (1) the "ground-transmitted" effects, and (2) the "air-induced" shock caused by local surface pressures. Except for locations of the order of less than 1.5 crater radii from the detonation, or in unusual circumstances of peculiar ground formations, the air-induced shock effects are substantially larger than those transmitted through the ground.

A summary of information concerning the maximum values of displacement, velocity and acceleration, in both vertical and horizontal directions at the surface and at various depths beneath the surface, may be found in Reference 1. Similar basic information is given in Reference 63. These effects are complex and are

influenced by the soil conditions the geological characteristics of the site, the presence of water, and other factors. Basic information in many aspects of the problem is lacking. Reference 22 is a valuable contribution to knowledge in this field.

5.2 Shock Mounting. Problems arise in the attachment of mechanical electrical and hydraulic equipment to a protective structure. The equipment must remain attached throughout a blast and must function in the post-blast state. Thus the attachments must have sufficient strength to transmit the forces which are associated with the equipment acceleration and with the relative distortion of structure and equipment. The maximum accelerations or displacements which can be tolerated by the equipment must be known or computed.

When the equipment must be connected to the structure at two or more points, and when significant relative displacements of these points are anticipated, and capacity of the equipment and attachments to sustain such movement must be ensured.

A detailed discussion on shock mounting of various types of equipment, piping etc. is given in Reference 64. In general it is desirable to provide as much flexibility in the mounting as possible, without sacrificing strength, in order to keep the response as low as possible, both for the equipment and the mounting itself.

6. Mechanical and Electrical Plant

6.1. Utility Services. The following are some of the important items which must be considered.

6.1.1. Ventilation. Fresh-air requirements for personnel should not exceed 20 cfm per person as a maximum for prolonged "button-up" periods: 10 cfm is usually sufficient. For short periods of a few days, it may be as low as 3 cfm per person if little physical activity is required; but supplementary odour removal equipment will be needed.

6.1.2. Refrigeration. Cooling requirements for all equipment, particularly electronic, should be carefully established in order not to require excess cooling capacity. Typical maximum cooling loads for Summer conditions are -

(a) Air Cooling and Conditioning

Communication equipment, computors vacuum tube, (transistorised equipment 25% less)	3400 BTU/hr/KW
Mechanical equipment (fans, conveyors)	2900 BTU/hr/KW
Lighting	2400 BTU/hr/KW
Power Plant facilities	370 BTU/hr/KW (KW of actual operational demand)
Ventilation (make-up air)	50 BTU/hr/cfm
Personnel	450 BTU/hr/person

(b) Diesel Generator Cooling — 2800 BTU/hr/KW (KW of actual operational demand)

The air cooling loads must be reduced to account for tolerable temperature rise during "button-up" operations and for losses to surroundings, particularly in the case of underground operations in rock. The cooling water demand for the air-cooling equipment is obtained by multiplying the air cooling load by a factor of 1.3.

6.1.3. Heat and Air-Conditioning. Normal comfort (i.e. 70°F, 50 to 60% R.H.) should be maintained for personnel for peace-time operations, but considerable discomfort is acceptable during "button-up" operations (50 to 90°F, 20 to 80% R.H.)

6.2. Water Supply. The absolute minimum of water supply is 1 gallon of drinking water per man day. It is recommended however that a minimum supply of 10 gallons/man day be planned for the "button-up" period and a more normal requirement is 100 gallons/man day. Water may also be required for industrial and cooling purposes and for sanitary flushings. The latter will normally amount to 10 gallon/man day. Chemical toilets can be provided for use during "button-up" periods in order to provide greater water supply for other use. Water supply is generally best obtained from wells drilled within the protected installation. If this is not possible, water well fields should be provided with blast resistant construction and a certain power source for pumping.

The storage of water for both domestic and industrial purposes will generally be necessary and should be located inside the installation protected against blast, chemical, bacteriological and radiological agents. Some of the water for industrial purposes may be located in surface reservoirs if contamination from fallout can be accepted.

6.3. Lighting and Electric Power. Lighting should be provided at approximately 40 ft. candles in administrative areas and may range from 5 to 50 ft. candles in other areas. Operation of the lighting system should be on an emergency circuit with an automatic transfer switch. Portable emergency lighting units of the re-chargeable battery-powered type should be provided in critical areas. For communications and other operational facilities which require large generating capacity and close power regulation, diesel engine generators should be considered as the primary and only source of power.

6.4 Sanitary Sewers. The sewage system should be so designed that the contaminated wastes may be delivered to a treatment facility, or if it is destroyed to a dumping area in such manner that blast and CBR agents cannot enter the protected installation through the pipe. Auxiliary chemical toilets should be provided.

6.5. Decontamination. To avoid chemical, radiological or biological contamination it is necessary to filter outside air drawn into the facility. Air for combustion engines need not be filtered if it can be kept to an isolated circuit. For fallout protection only, standard air-conditioning filters are used. Special filters are necessary for CW and BW protection. Filters must be protected by antiblast valves, which should have a fail-safe system for closure. Personnel decontamination facilities should be provided in at least two locations.

6.6. Fire Protection. Fires in confined spaces are difficult to control and likely to be devastating, and precautions against the initiation and spread of fires should be given due consideration in

the planning of installations. Areas with extreme fire hazards should be isolated and provision made to control the spread of fire or fumes by suitable doors.

Costs

7.1. Cost Estimation. According to Reference 1, experience in costs of protective construction is limited to a very small number of actual construction projects and relatively few design studies. Three types of estimate may be made from the available data.

(a) Gross Facility Estimate. This provides a single unit cost (price per square foot) for an entire facility, including all structural, mechanical, electrical elements, access, utilities etc. It can be used only in cases where the facility in question is typically the same as one for which actual construction costs experience is available.

(b) Detailed Cost Estimate. This requires a near-final design for the facility and consists of the procedures used conventionally in cost estimation. It is the most reliable but also the most lengthy method.

(c) Limited Cost Estimate. This reduces the total facility cost to a number of elements, for each of which unit costs are provided. The method is applicable to cases where the level of protection, size and general configuration of the facility are known, but advanced designs are not available and no direct experience data are available.

Table 1 taken from Reference 1 presents a list of the major elements which should be included in a limited cost estimate, and indicates unit costs which may be used in evaluating the contribution of each element. When a range of unit costs is given the estimator must select a value for a particular case.

The estimator must start with a design concept which includes the type and size of basic structure, and depth of cover. From these he must find the approximate excavation and fill quantities and the size of entrance structure. Figure 4 gives the variation of cost of basic structure as a function of type of structure. Figures 7, 8 and 9 show the variation for a particular structural type as a function of span or column spacing.

The additional costs of stairs or ramps in mounded or buried structures (included in Item 3 in Table 1) can be almost as costly as the basic structure, particularly when the latter is relatively small. Figures 4 and 5 are alike except that the curves in Figure 5 include the cost of the entrance structure, whereas Figure 4 does not. Figure 6 is not necessary to the use of Table 1 but is included for general reference.

Figure 10 gives approximate cost of protective doors per sq.ft. of opening, as a function of pressure and size. These cost curves also consider the attitude or orientation of the door in terms of whether it will be subjected to side-on reflected pressure. Costs of stairs, ramps or other access are not included in Figure 10.

Figure 11 indicates the estimated relative costs of underground and above-ground protective construction as a function of design overpressure. The cost factors given are not applicable to rock tunnel

type structures, which will be much more costly, particularly for design overpressures up to a few hundred psi. This figure does however indicate the relative cost between "cut and cover" and above-ground protective construction. It will be noted that above-ground protection becomes more expensive above about 40 psi.

7.2 Factors Affecting Costs. The most important aspects are summarised below:-

(a) Level of Protection. The strength and cost of structural components must increase with the overpressure level to be resisted, and the results of design studies of costs often have to be presented in the form of cost factors versus design overpressure. It should be noted however that overpressure is not always the governing factor in costs from the point of view of protection level. In particular, for surface structures designed to low overpressure levels, protection against radiation hazards (in the form of minimum thickness of structural components and provision for air filtering) may be more important than overpressure levels.

(b) Size. From the point of view of direct structural costs the required size, particularly the required clear span, is very important. Figure 7 indicates the influence of clear span on costs for a simple rectangle form of structure. The question of size is also bound up with the function of the construction; for example the floor space provided in arched and domed structures is related to the size of the structure and whether multi-level floor systems can be used. For certain cases, such as aircraft shelters, the necessary span and particularly large door requirements dominate the costs.

(c) Number of Personnel and Duration of Occupancy. Human occupancy adds much to the cost of protective construction. Utilities, messing facilities, food and water storage, air-conditioning are costly items dependent upon the number of occupants and the duration of their stay.

(d) Function. All other listed factors are directly or indirectly related to the function of the installation. Both day-to-day and attack conditions of operation may be significant from the cost of viewpoint. The requirements for utilities, ventilation, entrances, etc. may vary from the minimum in the case of a warehouse to a maximum in the case of a missile base or command centre.

(e) Geological Area and Site Location. Factors which influence the cost of conventional construction are at least equally important to the cost of protected construction. Proximity to transport, power and water, and the local availability of labour and materials are such factors.

The cost of protective construction may be more sensitive to conditions at the specific site. The type of soil to be handled is a major factor in costs of excavation and foundations, and the importance of this factor increases with depth of construction. Ground water may add greatly to the costs of construction operations and entail additional expense for waterproofing the structure.

Whether a particular construction is isolated or part of a complex may influence direct construction costs, as well as mechanical and electrical costs for the finished installation. Similarly the distance between the structures in a complex may influence direct and indirect construction costs.

7.3. Cost of Aircraft Protection. Some recent British and U.S. estimates of the cost of aircraft shelters have been stated (References 55 and 57).

The U.K. paper (Reference 57) estimates the structural cost of a bomber aircraft shelter to withstand 15 psi overpressure as about £0.5m. This would be an above-ground shelter. An underground installation for a bomber, able to withstand 100 psi is estimated at about £1.0m.

The cost of an underground structure giving protection up to 100 psi for aircraft such as the F.104 is estimated to be about $0.5m. (Reference 55).

TABLE I

COST DATA FOR LIMITED COST ESTIMATES

Item	Costs (cy = cubic yard, S.F. = sq.ft., L.F. = lin. ft.)			
	Above Ground	Mounded or Shallow u/g (25' cover)	Deep Underground	Remarks
1. Excavation and Backfill	Dollars/cy	Dollars/cy	Dollars/cy	
Backfill	2	3	–	
Excav. Earth	3	3	6	
" Soft Rock	6	6	15	
" Hard Rock	10	10	25	
" Added cost if ground water problem	–	Add 50%	Add 100%	
2. Structural	Dollars/S.F.	Dollars/S.F.	Dollars/S.F.	
Walls, roof, floors and foundations, building frame and cladding, exclusive of interior partitions, finishes and excavation	9 (soft) See Figures 4, 7, 8, 9	See Figures 4, 7, 8, 9	Unlined 20 Lined 25	Structural costs vary with structural type, span, and design overpressure
3. Entrances, Doors	(See Figures 4, 5 and 10) Add 3 dollars/ S.F. of door for radiation shielding at 25 p.s.i.	(See Figures 4, 5, and 10) Add for stairs or ramps	(See Figures 4, 5 and 10) Multiply by factor 1.5; access tunnels under Item 7	
4. Architectural (Interior finishes, partitions, etc.)	4 – 9	4 – 9	10 – 22	Lower figures apply to simple interior layout, higher figures to multipartitional layout, acoustic treatment, etc.
5. Mechanical	Dollars/S.F.	Dollars/S.F.	Dollars/S.F.	Includes 1.50 dollars/S.F. for decontam., air filt., blast valves, etc. Refrigeration costs for cooling electronic equipment, and ice storage for emergency used must be added
(Heating, ventilating, air conditioning, air filtration, plumbing)	4 – 7	4 – 7	5 – 8 But add to excav. and struct. costs	
6. Electrical				
(Lightning, electrical outlets, normal power connections)	3 – 5	3 – 5 But add to excav. and struct. space	4 – 6 But add to excav. and struct. costs	Includes 1.0 dollars/S.F. for minimum admin. standby. For operational standby add 300 dollars/K.W. for generators and switchgear.
7. Water Supply; Sanitary; Ventilation shafts and tunnels; Personnel shafts and tunnels	250 dollars/ person for water; 350 dollars/person for sewerage; 20 D dollars/S.F. (for D = 10' dia.) 30 D dollars/L.F. (for D = 10' dia;)	Same as for above ground	350 dollars/person for water 450 dollars/person for sewerage	For shafts and tunnels, cost of excav. or tunnelling must be added.
8. Site Improvements				
Access Roads, Power transmission, Communications, etc.				

NOTE: All costs are referred to 1959 indices (U.S.) and Geographical Factor of 1.0.
Costs consist of contract costs plus about 20% for contingencies and inspection.

A. General Design Studies

Ref. No.	U.K. Reference	U.S. Reference	Author	Title	Security Classn.	Remarks
1.	Home Office CD 12237	OASD (P & I)	N.M. Newmark R.J. Hansen M.J. Holley J.M. Biggs	Protective Construction Review Guide - Unclassified Extracts issued for University of Illinois and M.I.T. Jan. 1959	U	Very useful general review, with bibliography.
2.	DGAW 764/60	ASTIA Document AD 150659 R and S-69	Rand Corp.	Proceedings of the Symposium on Protective Construction May 1957	Secret Atomic	
3.	TIL Numbers P.57300 and P.57301	U.S. Army Contract DA-49-129-eng-120	Amman and Whitney	Design of Structures to Resist Atomic Blast 2 vols.	C	A very detailed study
4.		Bull. Virginia Polytech. Inst. Eng. Ext. Station No. 106	N.M. Newmark	Analysis and Design of Structures to Resist Atomic Blast Jan. 1956	U	
5.	DGAW 387/60	Trans.Amer.Soc. Civ. Eng. 121 1956, pp.45-64	N.M. Newmark	An Engineering Approach to Blast Resistant Design	U	A simplified study of design essentials
6.	MEXE, A.D.292	BuDocks Instruction 3441.2, Sup -1	U.S.N. Bureau of Docks and Yards	Studies in Atomic Defence Engineering	U	
7.	MEXE, AD.295 Home Office CD 12336	Atomic Defence Eng.Tech. Study 28	W.J. Christensen (U.S.N. Bureau of Docks and Yards)	Relative Vulnerability of Underground Protective Construction Sept. 1959	U	
8.		Atomic Defence Eng. Tech. Study 27	W.J. Christensen	Air Blast Induced Ground Shock	U	
9.		Civil Eng.Studies Structural Research Series, No. 149	J.L. Merritt N.M. Newmark (University of Illinois)	Design of Underground Structures to Resist Nuclear Blast		
10.		Armour Research Foundation. Final Report on Proj. K.149	K.E. McKee R.W. Sauer	Evaluation of Deep Tunnel Shelters Nov. 1958	U	
11.		Draft Engr. Manual Military Construction EM 1110-345-421		Design of Structures to Resist the Effects of Atomic Weapons, Buried and Semi-Buried Structures		
12.	DGAW 283/60	Contract DA-49-129-eng-312	J.L. Merritt G.F. McDonough N.M. Newmark	Evaluation of Data from Underground Explosion Tests in Soil. Vol. I, Final Report, May, 1958	C Atomic	
13.	DGAW 622/60	"	J.L. Merritt N.M. Newmark	Vol. II, Design of Underground Structures to Resist Nuclear Blast	U	
14.		Armour Research Foundation, Final Report on Project K.138		Study of the Feasibility of Tunnel Closures to Resist Nuclear Blast Aug. 1958	U	
15.	MEXE, AD.297	Eng.Manual Mil. Constr. Part XXV		Chapters 1-6. Heating and Air Conditioning of Underground Installations (1956)		
16.	MEXE, A.D. 298-305	U.S. Army Corps of Engineers Manuals EM 1110-345-413, 414, 415, 416, 417, 419, 420, 461	M.I.T.	Series of U.S. Army Manuals dealing with the design of structures to resist the effects of atomic weapons	U	
17.	Home Office CD 12412		D.G. Christopherson	Theoretical Treatment of Blast Induced Earth shock	C	

A. General Design Studies (Contd.)

Ref. No.	U.K. Reference	U.S. Reference	Author	Title	Security Classn.	Remarks
18		Dept. of Navy, Bureau of Docks and Yards, Tech. Study No. 24	C. Curione	Cost Guidance for Protective Construction 20 Aug. 1958	U	Ref. from "Protective Construction Review Guide"
19		Office of Civil and Defence Mobilisation		Guide for Fallout Shelter Surveys (Interim Edition, Dec. 1958)	U	- ditto -
20	AWRE Report E1/57		P. Chadwick	Estimates of the Incident Stress upon Buried Shelters from Megaton Bombs	C	
21	TIL No. P 84316	AFSWC-TN-58-23 (Stanford Res. Inst.)	F.M. Sauer G.W. Evans C.M. Alblow J.L. Brenner	Ground Motion Induced by Nuclear Explosions. A study of Fundamental Problems Nov. 1958	C	
22	DGAW 598/60	Stanford Res. Inst. Project SU-2206, AFSWC-TR-59-71	F.M. Sauer	Ground Motion Produced by Above-ground Nuclear Explosions.	Secret Atomic	
23		Rand Corporation R-34		Proceedings of the Second Protective Construction Symposium Vols. I and II March 1959	U	
24		Rand Corporation RM-1777	P. Weildlinger	Practical Estimated Limits of Blast Resistant Steel Shelters May 1957	U	
	B. General Target Response Information and Effects on Electronics					
25	D1/57 Target Response Manual		D.G.A.W. Min. of Aviation	Damage by Nuclear Weapons	C Discreet	
26		TM23-200	D.A.S.A.	Capabilities of Atomic Weapons	C	
27	DGAW 294/60	ITR-1637	E.E. Conrad (D.O.F.L.)	Effects of Nuclear Radiation on Electronic Fuze Components and Materials	Secret Atomic	
28	A.W. Plans Note 25		A.W. Plans Min. of Aviation	Nuclear Hazards to Transistors	Secret	
29	A.W. Plans Note 34		DSRL/A.W. Plans Min. of Aviation	Transient Effects on Electronics with Pulsed Nuclear Radiation	Secret Discreet	
30	A.W. Plans XY/222/05		P. Haas (D.O.F.L.)	U.S./U.K. Weapons Effects Conference July, 1959 - Panel B Weapon Effects on Electronic Components		

C. Trials Reports

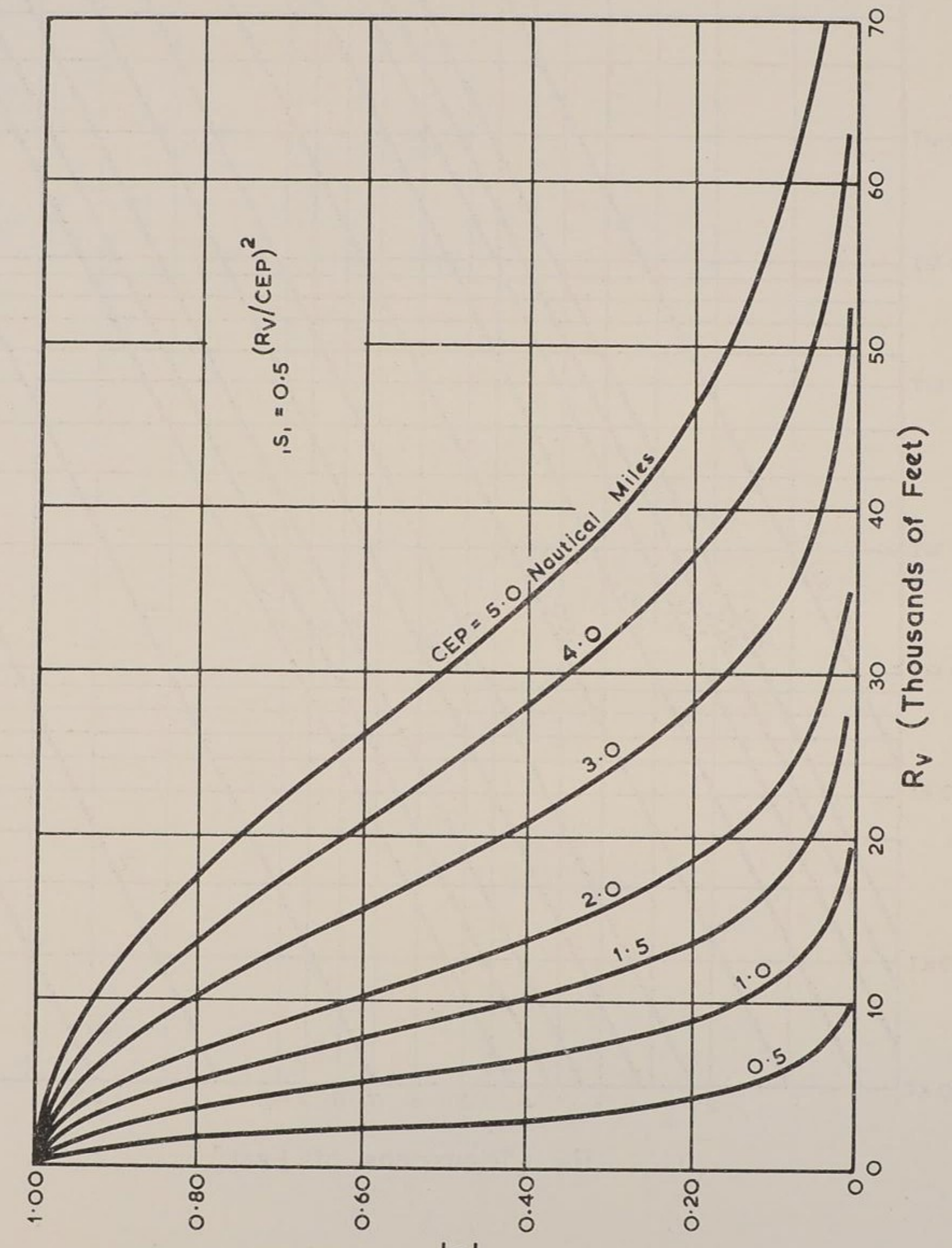
Ref. No.	U.K. Reference	U.S. Reference	Author	Title	Security Classn.	Remarks
31	AWRE Report T 47/57		A.J. Wood	The Effect of Earth Covers on the Resistance of Trench Shelter Roofs	C	
32	AWRE Report T 37/57		J.K. Wright	Operation Buffalos. Measurement of Ground Shock and Crater	Secret	
33	AWRE Report T 42/58		A.G. Hunt	Operation Antler. Measurement of Ground Shock	C	
34		WT - 727		Operation Upshot-Knothole. Air Blast Effects on Underground Structures	C	
35		WT - 1127		Operation Teapot. Air Blast Effects on Underground Structures	C	
36		WT - 1128		Operation Teapot. Evaluation of Earth Cover as Protection to Aboveground Structures	C	
37		ITR-1404		Operation Plumbbob. Ground Acceleration, Stress, and Strain at High Incident Overpressures	C	
38		ITR 1405		Operation Plumbbob. Ground Motion Studies at High Incident Overpressure	C	
39	DGAW 565/60	WT - 1420		Operation Plumbbob. Blast Loading and Response of Concrete-Arch Protective Structures	C	
40		WT-1424		Operation Plumbbob. Isolation of Structures from Ground Shock.		
41		WT-1425		Operation Plumbbob. Full-scale Field Tests of Dome and Arch Structures		
42		ITR-1447		Operation Plumbbob. The Internal Environment of Underground Structures subjected to Nuclear Blast. I - The occurrence of dust	O.U.O.	
43	DGAW 67/59	ITR-1448		Operation Plumbbob. Field Test of Reinforced Concrete Dome Shelters and Prototype Door	O.U.O.	
44		ITR-1449		Operation Plumbbob. Response of Dual-purpose Reinforced Concrete Mass Shelter	O.U.O.	
45		ITR-1459		Operation Plumbbob. Evaluation of Industrial Doors Subjected to Blast Loading	O.U.O.	
46		ITR-1460		Operation Plumbbob. Test and Evaluation of Anti-Blast Valves for Protecting Ventilation Systems	O.U.O.	
47		ITR-1475		Operation Plumbbob. Blast Effects on Air-Cleaning System	O.U.O.	
48	DGAW 296/60	ITR-1613		Operation Hardtack. Ground Motion Produced by Nuclear Detonations	Secret Atomic	
49		ITR-1631		Operation Hardtack. Damage to Existing EPG Structures	Secret	
50	Home Office C. 12398	ITR-1703		Operation Hardtack. Surface and Sub-surface Strong Motion Measurements	U	
51		ITR-1714		Operation Hardtack. Evaluation of Blast and Shock Effects on Tunnel Support Structures.	U	

D. Special Studies of Aircraft Shelters

Ref. No.	U.K. Reference	U.S. Reference	Author	Title	Security Classn.	Remarks
52	DGAW 572/60	SADTC Report 1960/R-4	J. L. Jenkins	Passive Defense Techniques for NATO Strike Aircraft Vol. I. Staff Summary	NATO SECRET	
53	DGAW 573/60	1960/R-5		Vol. II Comparative Evaluation		
54		1960/R-6		Vol. III Hardening		
55	DGAW 350/60	SADTC Paper for 5th SHAPE OR/SA Conference	J. L. Jenkins	Hardening and Other Passive Defense Techniques	NATO SECRET	Basically the same as SADTC Report 1960/R-4
56	DGAW 348/60	USAFE Ops. Analysis Office. Paper for 5th SHAPE OR/SA Conference	H. K. Gayer	Ground Survivability of Nuclear Strike Aircraft	NATO SECRET	
57	DGAW 349/60 Air Ministry paper for 5th SHAPE OR/SA CONF.		J. R. Laville	The Relative Effectiveness of Hardening and Dispersal for the Protection of VTOL Aircraft in the U.K.	NATO SECRET	
58		Contract AF 18 (600) - 1636 for AFSWC		A Protective Alert Shelter for Strategic Air Command 1st April 1957	SECRET	Listed in bibliography of "Protective Construction Review Guide"
	E. Special Studies of Rocket Launchers					
59	DGAW 383/60		J. K. Wright E. W. Carpenter	The Effect of Ground Shock on the Blue Streak Missile Launcher 25th June, 1958	SECRET	A.W.R.E. paper
60	DGAW 382/60		G. W. Dept. R.A.E.	Blue Streak R. & D. Requirement Paper No. 1, Issue 2, Nov. 1959. Underground Emplacement - Shock due to Nuclear Attack.	SECRET	
61	DGAW 381/60		Air Ministry (D.G.W.)	Report on a Visit by United Kingdom Air Ministry Team to U.S.A., Feb. 22 - March 6, 1959	SECRET	Study of Underground Installations and facilities for TITAN missile.
62		Contract AF-04(647)-156 American Machine and Foundry Co.		Final Report of Special Studies Related to WS 107A-2 Launcher Vol. II. Ground Shock, Structure Response and Thermal Radiation (6 August, 1958)	SECRET	Listed in bibliography of "Protective Construction Review Guide"
63				Vol. III. Considerations in the Design of Underground Protective Structures (20 June, 1958)	SECRET	
64				Vol. IV. Shock Effects on Equipment (15 August, 1958)	SECRET	
	F. AWRE Ground Shock Reports					
65	AWRE Report 0-19/54		J. K. Wright J. D. Herbert	Considerations leading to a programme for the study of ground shock and the necessary instrumentation.	C	
66	AWRE Report 0-20/54		J. K. Wright J. D. Herbert	Measurement of ground shock in unconsolidated clay. Part 1. Surface movements due to a charge detonated on the ground.	C	
67	AWRE Report 0-21/54		J. K. Wright J. D. Herbert	Measurement of ground shock in unconsolidated clay. Part 2. The effect of detonating a charge above and below the ground.	C	

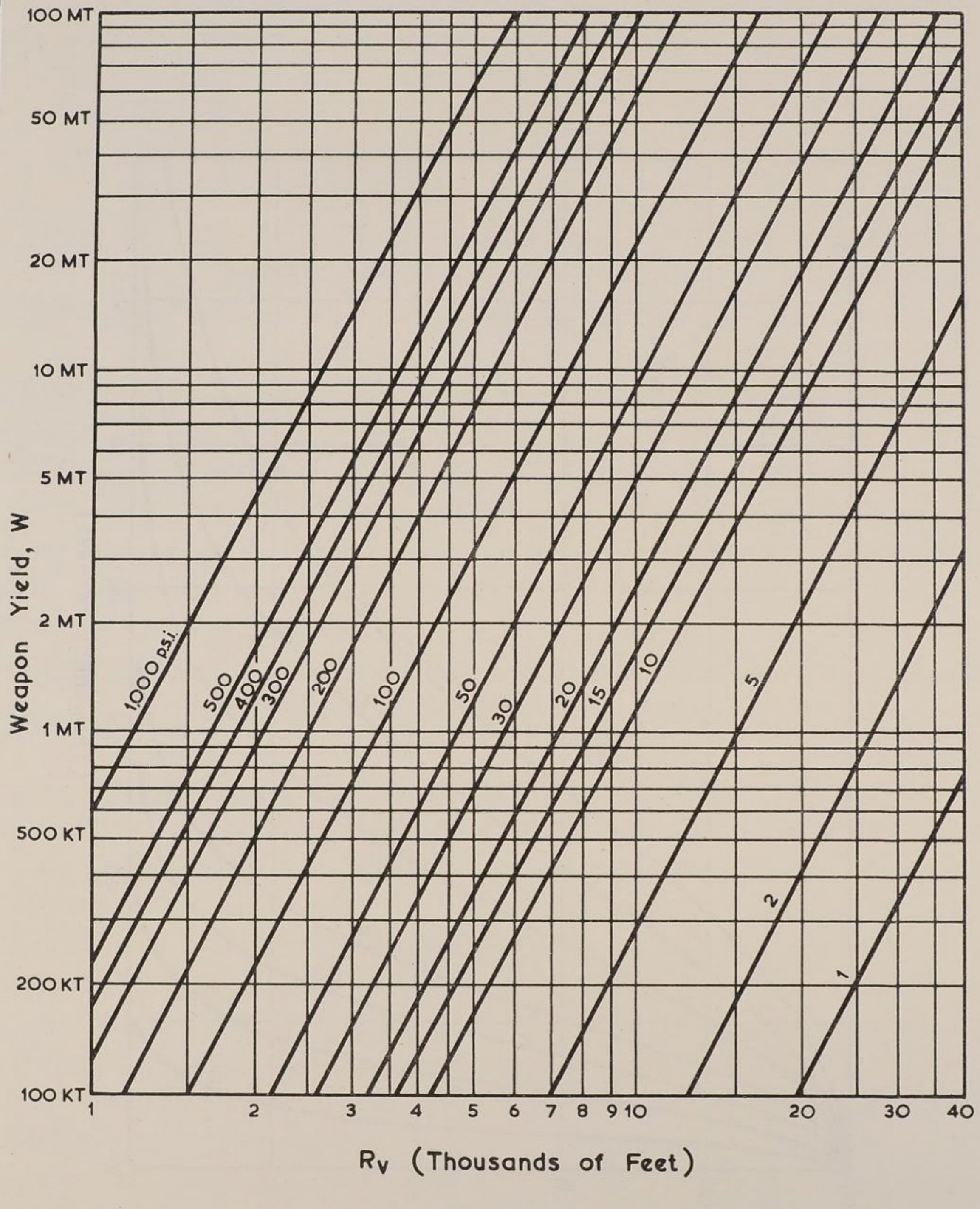
F. AWRE Ground Shock Reports (continued)

Ref. No.	U.K. Reference	U.S. Reference	Author	Title	Security Classn.	Remarks
68	AWRE Report 0-40/55		J. K. Wright J. D. Herbert	Measurements of ground shock in various media. Interim report on charges fired on the surface.	C	
69	AWRE Report 0-25/56		J. K. Wright J. D. Herbert	Measurement of ground shock in homogeneous media. Part 1. The surface movement due to a 2 oz. charge detonated on the ground.	C	
70	0-28/57		J. K. Wright J. D. Herbert	Measurement of ground shock in homogeneous media. Part 2. The surface movement due to a 2 oz. charge detonated above or below the surface.	C	
71	0-60/57		J. K. Wright	A theory of movement in the ground caused by the passage of air blast over the surface.	C	
72	0-16/59		E. W. Carpenter J. A. McDonald P. D. Marshall	Small scale ground shock experiments on a two-layer stratified medium.	C	

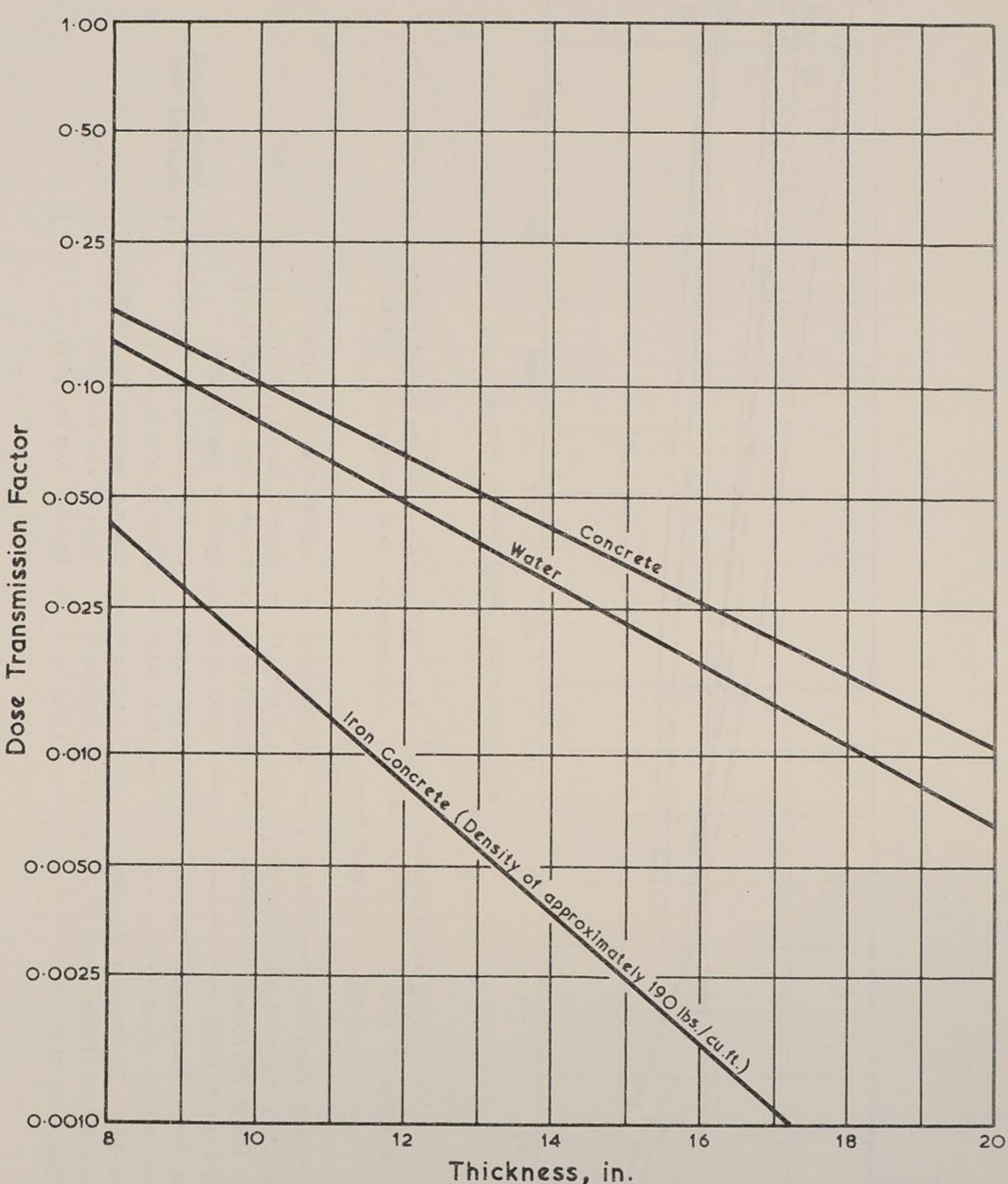


SINGLE ATTACK SURVIVAL PROBABILITY VERSUS VULNERABILITY RADIUS FOR SINGLE TARGET WHICH IS THE AIMING POINT.

PART IV
CHAPTER 6
FIGURE 2

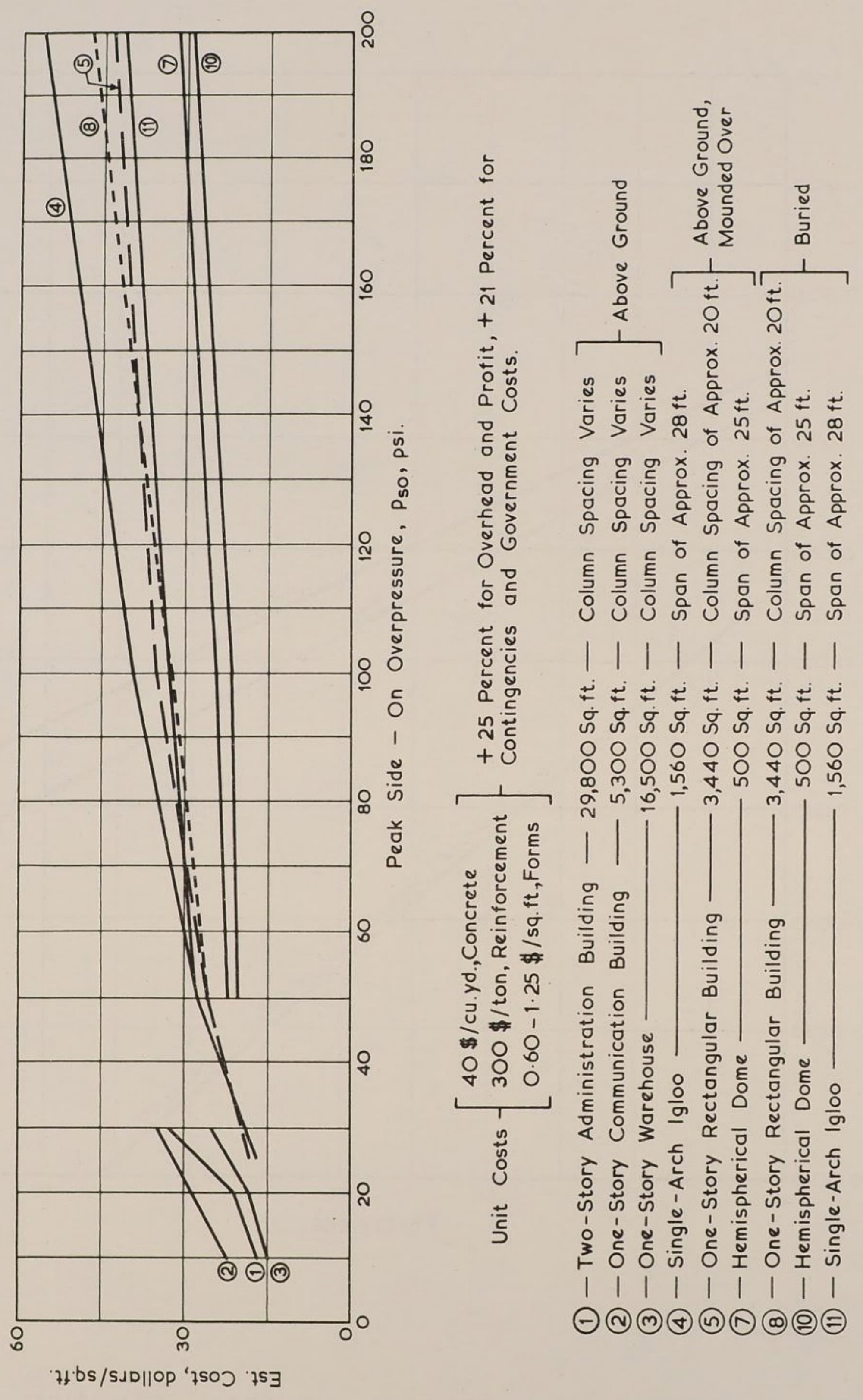


WEAPON YIELD VERSUS VULNERABILITY RADIUS FOR VARIOUS SIDE-ON OVERPRESSURES AT GROUND SURFACE — SURFACE BURST, SEA LEVEL

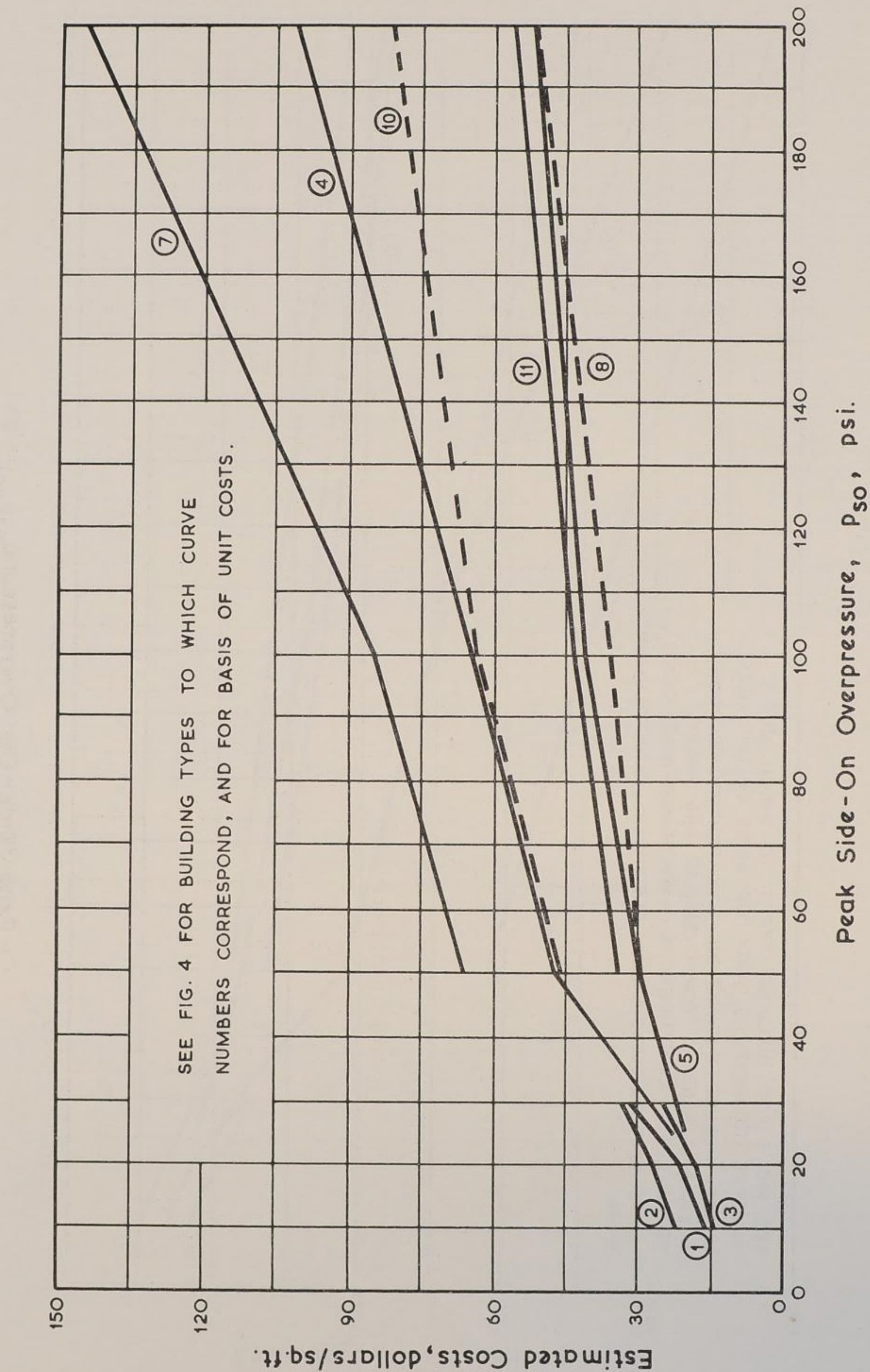


ATTENUATION OF FAST NEUTRON RADIATION —
BROAD BEAM IN THICK SHIELDS.

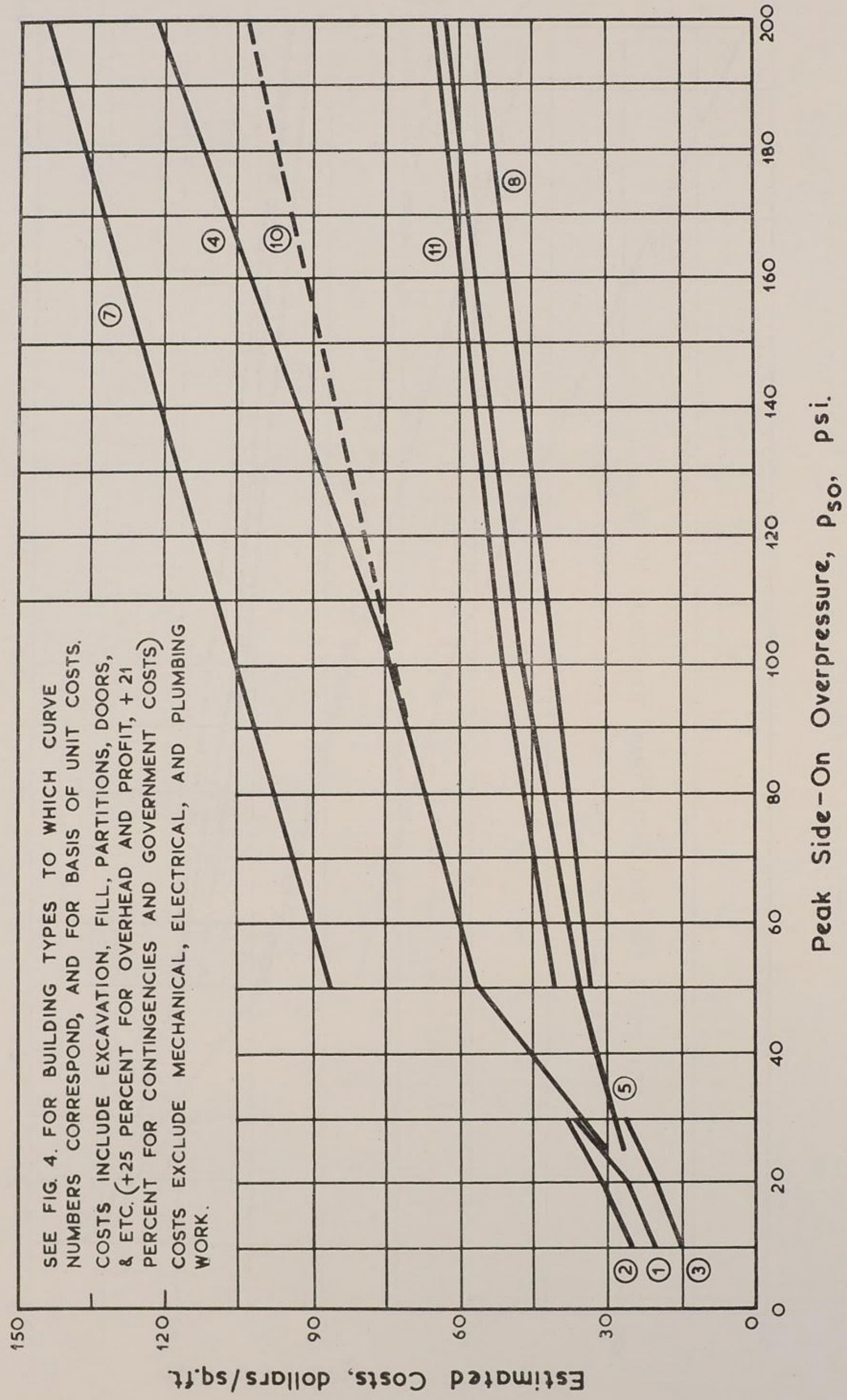
PART IV
CHAPTER 6
FIGURE 4



ESTIMATED COST OF BARE STRUCTURE, EXCLUDING ENTRANCE STRUCTURES



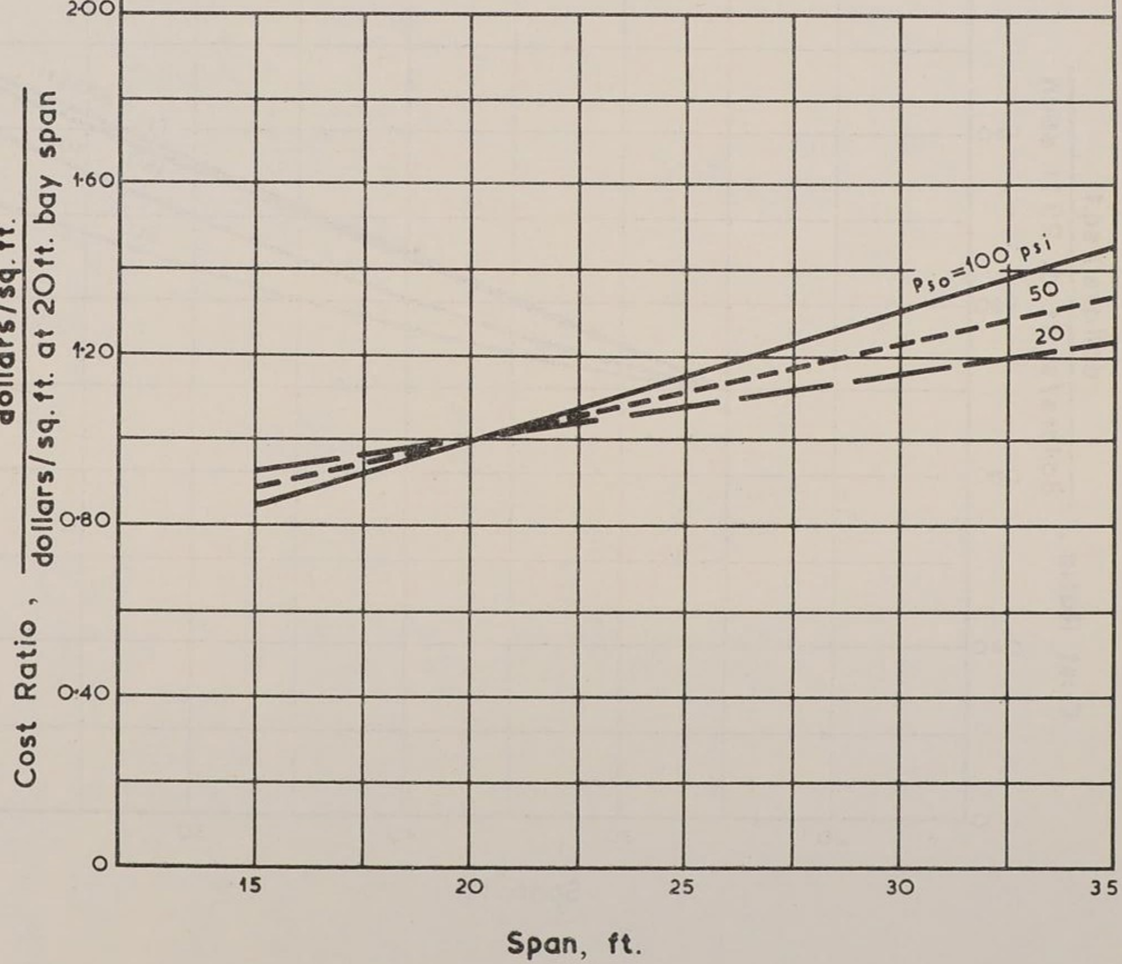
ESTIMATED COST OF BARE STRUCTURE, INCLUDING SPECIAL ENTRANCE STRUCTURES.



ESTIMATED COST OF STRUCTURES

BASIS: COST STUDIES OF BURIED AND SURFACE ONE-STOREY SQUARE STRUCTURES, WITH VARYING BAY SPANS. SPECIAL ENTRANCES AND EXCAVATION NOT INCLUDED. BARE STRUCTURE ONLY (CONCRETE, STEEL, AND FORMWORK.)

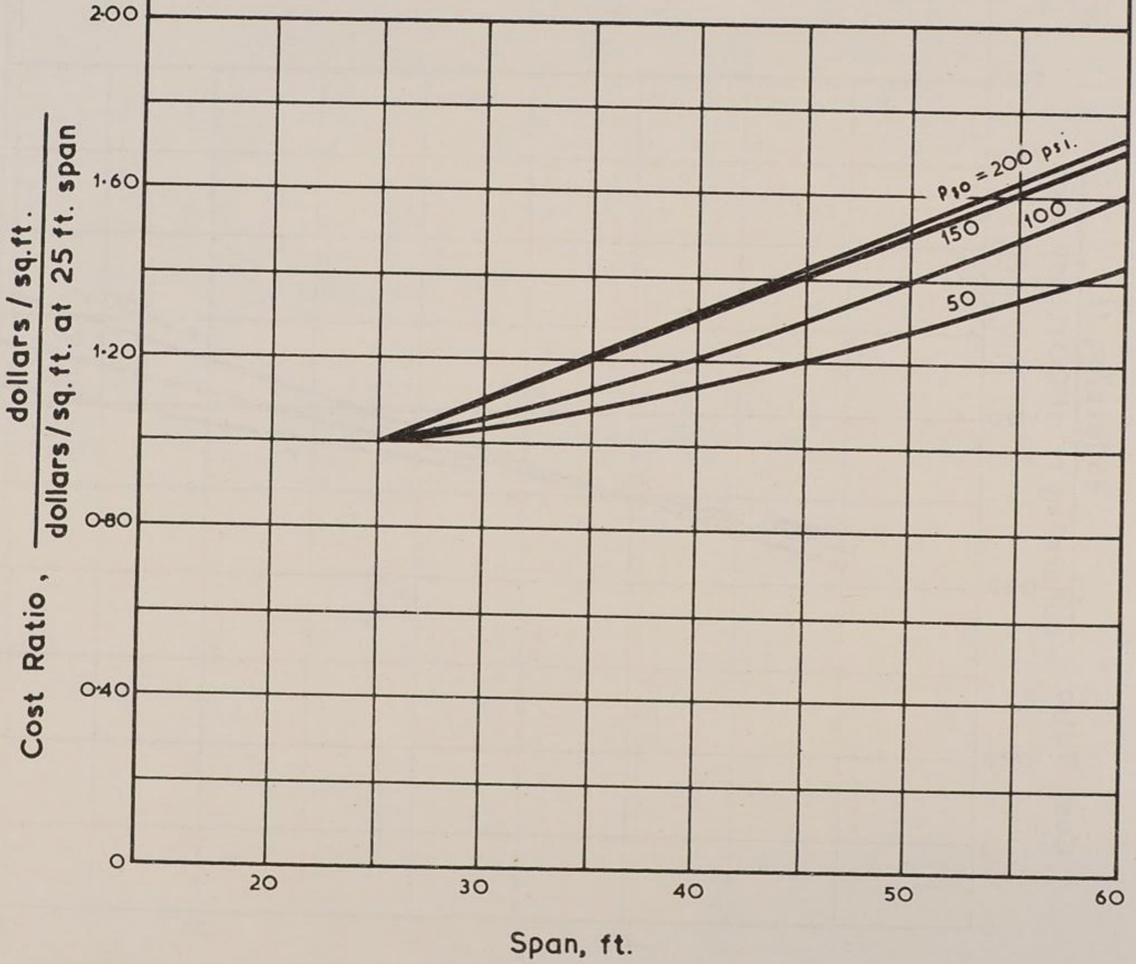
NOTE: FOR INDEX COSTS USE CURVES (2), (3), (5), AND (8), OF FIG. 4



COST RATIO VERSUS SPAN FOR ONE-STOREY RECTANGULAR STRUCTURES

BASIS: COST STUDIES FOR BURIED HEMISPHERICAL DOMES. SPECIAL ENTRANCES AND EXCAVATION NOT INCLUDED. BARE STRUCTURE ONLY (CONCRETE, STEEL, AND FORMWORK.)

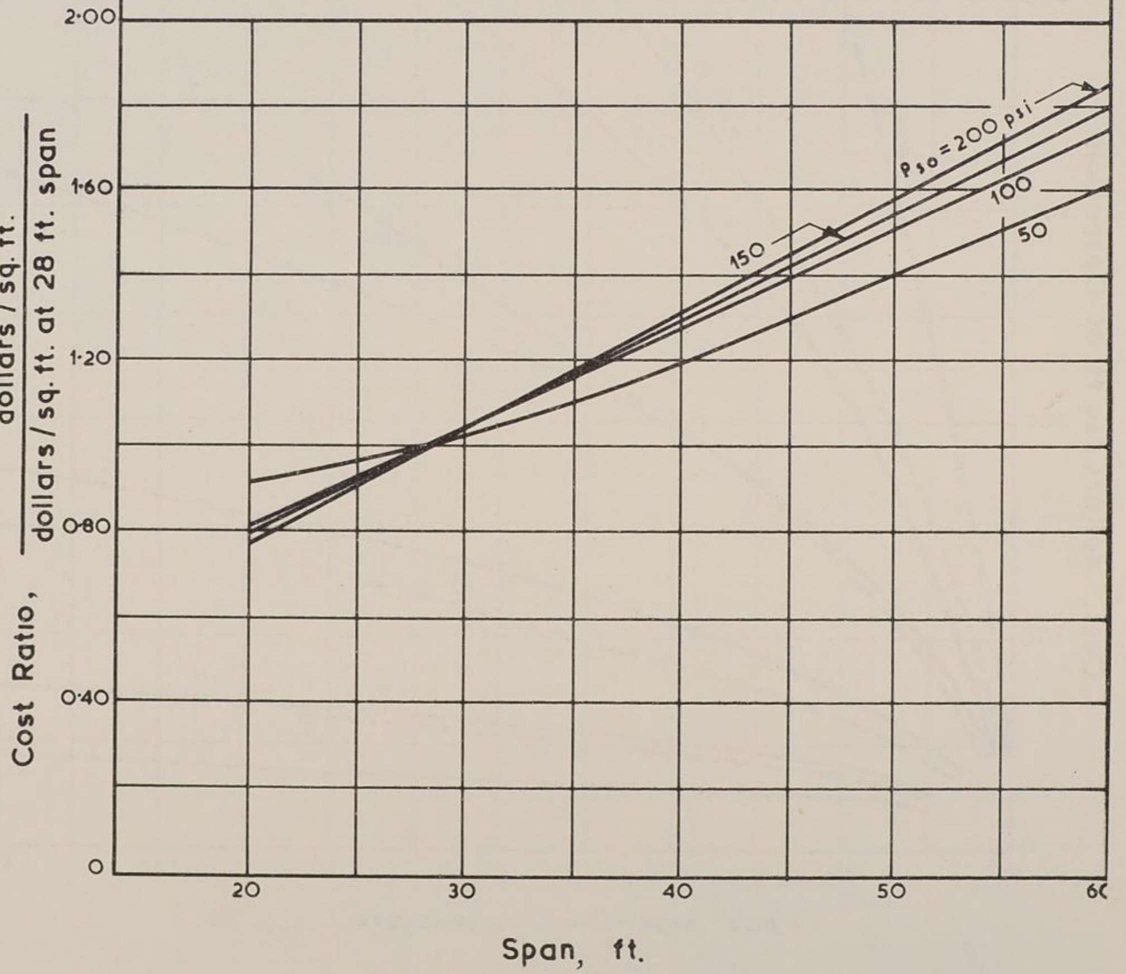
NOTE: FOR INDEX COSTS USE CURVES (7) AND (10) OF FIG. 4



COST RATIO VERSUS SPAN FOR DOME STRUCTURES.

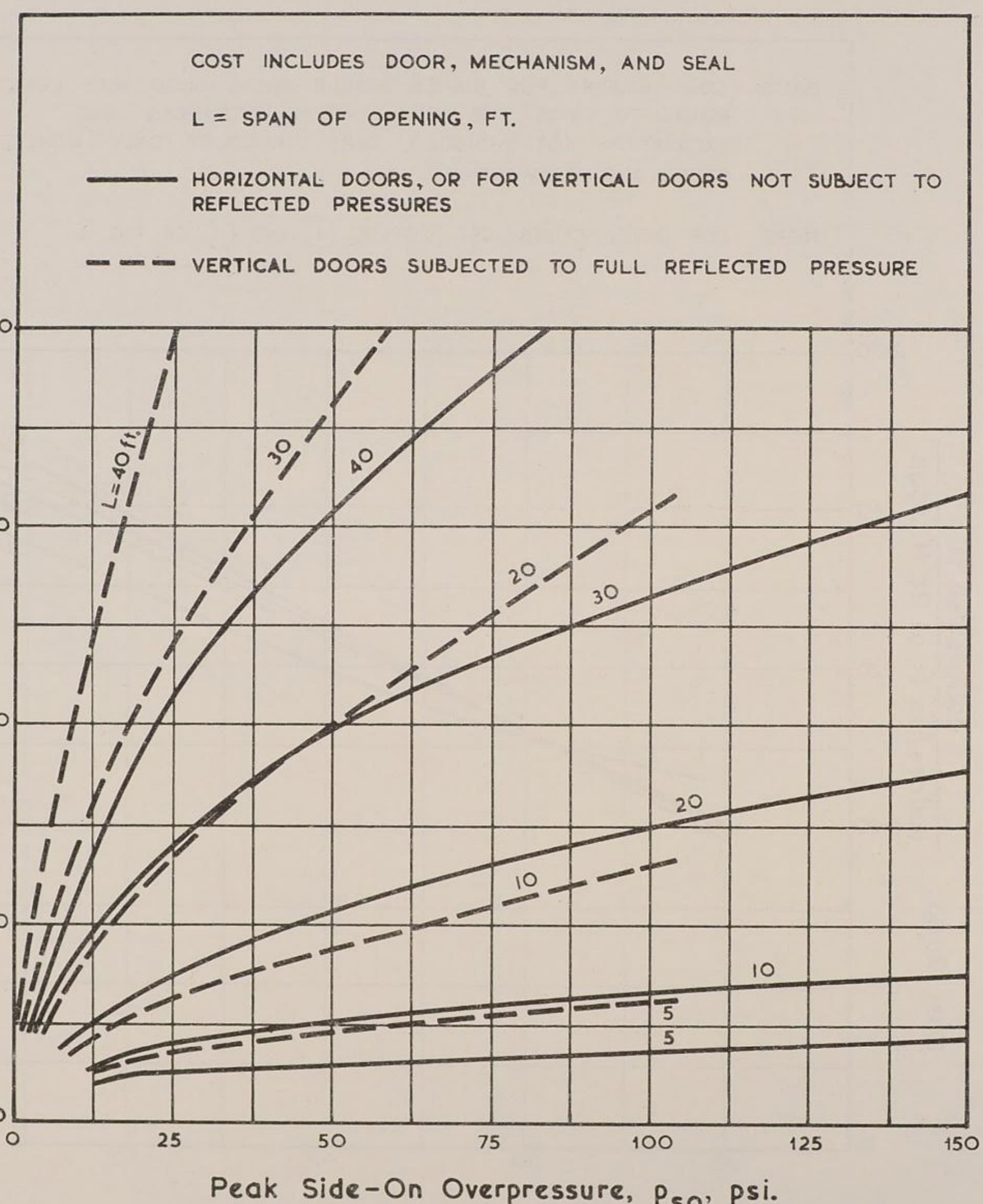
BASIS: COST STUDIES FOR BURIED, SINGLE-ARCH, IGLOO WITH LENGTH EQUAL TO TWICE THE SPAN. SPECIAL ENTRANCES AND EXCAVATION NOT INCLUDED. BARE STRUCTURE ONLY (CONCRETE, STEEL, AND FORMWORK.)

NOTE: FOR INDEX COSTS USE CURVES (4) AND (11) OF FIG. 4.

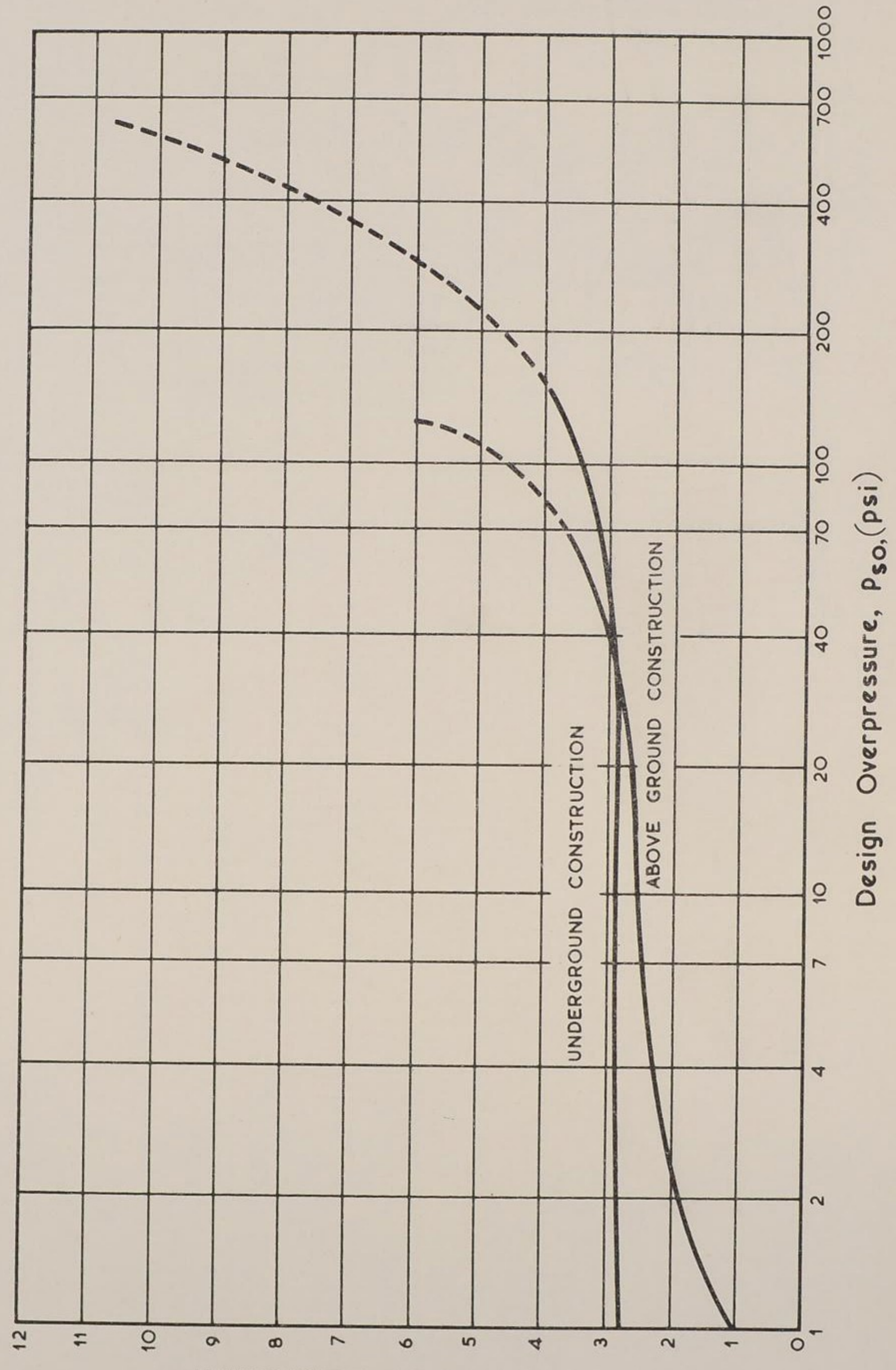


COST RATIO VERSUS SPAN FOR ARCH (IGLOO) STRUCTURES.

PART IV
CHAPTER 6
FIGURE 10



COST OF PROTECTIVE DOORS



RELATIVE COST OF CONSTRUCTION VS DESIGN OVERPRESSURE

PART V - DAMAGE BY UNDERWATER EXPLOSIONS

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Symbols and Units

a = Radius of cylinder (in.)

c = Velocity of sound in water (5000 ft./sec.)

D = Depth of burst (ft.)

d = Depth of target or measuring point or draught of ship (ft.)

E = Shock wave energy flux in free water (p.s.i. in.)

E_H = A suggested measure of the energy available to do damage to ship's side plating (p.s.i. in. or ft.lb./ft.^{2}).

E_v = A suggested measure of the energy available to do damage to ship's bottom plating (p.s.i. in. or ft.lb./ft.^{2}).

E_τ = Shock wave energy flux up to time of cut-off (p.s.i. in. or ft.lb./ft.^{2}).

H = Horizontal Range from point of burst (ft.).

I = Shock wave impulse in free water (p.s.i. sec.)

m = Mass/unit area of plating.

P_c = Static collapse pressure (p.s.i.).

P_m = Peak shock wave overpressure (p.s.i.).

P_o = Hydrostatic pressure (p.s.i.).

P_r = Pressure ratio = $(P_m + P_o)/P_c$

p_i = Shock wave overpressure $(p_i = P_m e^{-t/\theta})$

p_r = Reflection pressure (p.s.i.).

R = Slant Range from point of burst (ft.).

S = Frame strength parameter.

t = Time (usually millisecs.).

t_1 = Time after shockwave arrival at which shock wave incident pressure plus hydrostatic pressure equals the collapse pressure.

= $\ln [P_m/(P_c - P_o)]$.

V_h = Maximum horizontal velocity of ship's side plating (ft./sec.).

V_v = Maximum vertical velocity of ship's bottom plating (ft./sec.).

v = Velocity (of water particle, plate, cylinder etc.) (in./sec. or ft./sec.).

W = Total energy release in an explosion (Kilotons).
1KT = 10^{12} calories total energy release = energy released by the detonation of 1000 short tons of T.N.T. The energy available for producing shock waves is taken as $(\frac{2}{3})$ W. The energy available for producing bubble phenomena is taken as (0.86)W.

w = Weight of a T.N.T. charge (lb.). If w is the equivalent weight of an atomic bomb of total yield W then

$w = (1.33)10^6 W$ for shock wave effects

$w = (1.72)10^6 W$ for effects associated with bubble behaviour.

x = Distance measured from a plate along its normal.

$z = \dfrac{m}{\rho c \theta}$

α = Angle that normal to shock front makes with horizontal, plate, or water surface.

β = P_o/P_c.

γ = Parameter defining the relation of lethal stand-off to depth of submergence for submarines (see Section 4.5 equation 9).

θ = Shock wave decay constant (millisecs.).

ρ = Density of water = $(0.96)10^{-4}$ (lb.in.sec. units).

ρc = Acoustic impedence of water = 5.76 (lb.in.sec. units).

τ = Cut-off time (millisecs.) = Time at which the shock wave pressure is reduced to near zero due to the effect of reflection at the free surface. $\tau \approx (0.4)Dd/R$ (millisecs).

CHAPTER 1 - INTRODUCTION

The explosion underwater of nuclear weapons results in a fireball composed of the vapourised bomb and vapourised water, at great temperature and pressure. The high pressure of the fireball generates a shock wave which radiates away from the point of detonation, and the fireball gases form a bubble as they expand against the hydrostatic pressure. At this stage the phenomena resemble those resulting from the underwater detonation of high explosives, and it is known from full scale trials that the shock wave and bubble effects at ranges of interest to target response can be described by substituting a T.N.T. charge of a given weight.

The shock wave and bubble pulse phenomena resulting from the underwater explosion of T.N.T. are well known and are described in detail in Data Sheet 4.2. etc. of the "Manual on the Effects of Atomic Weapons." For this reason only a very brief description of these phenomena is given below.

The shock wave in unrestricted water decays exponentially with time for at least one time constant and the peak pressure falls off with radial distance R as $R^{1.13}$

The pressure-time relationship for the shock wave in unrestricted water at a distance R (ft.) from the point of burst may be written

$$p_i = P_m e^{-t/\theta} \quad t > 0 \tag{1}$$

$$p_i = 0 \quad t < 0 \tag{2}$$

where p_i is the shock wave pressure at time t at a fixed distance R (ft.)

P_m is the peak shock wave pressure at this distance

$$P_m = (4.38)10^6 (W^{1/3}/R)^{1.13} \text{ (p.s.i.)} \tag{3}$$

θ is the time constant (or decay constant)

$$\theta = (2.83)W^{1/3}(W^{1/3}/R)^{-0.18} \text{(m sec)} \tag{4}$$

t is time measured from the time of arrival of the shock wave at the distance R in the same units as θ

It is of interest to note that, unlike the airburst case, the shock wave phase is associated with only positive overpressures. Much smaller negative overpressures of very long duration (can be longer than 1 second for 1 K.T.) associated with the overshoot of the gas bubble would occur in unrestricted water, but the mechanism of formation is rather different from that of the suction phase associated with an airburst. The long duration suction phase of an underwater burst will always be effectively destroyed by surface cut-off in practical cases.

Except in the anomalous region mentioned below the effect of the surface of the sea can be calculated by postulating an exactly similar but negative pressure pulse originating simultaneously at the image point of the detonation position with respect to the sea surface. The effect of this negative pressure is to reduce the shock wave pressure to zero at a time given approximately by (0.4)Dd/R milliseconds where D is the detonation depth, d is the depth of the point under consideration and R is the distance between the two, all measured in feet. The inability of sea water to withstand large tensions prevents the occurrence of significant negative pressures.

The impulse and energy in the shock wave passing a given point up to the time of cut-off are given by

$$I = (12.4)10^3 W^{1/3}(W^{1/3}/R)^{0.95}\left[1 - e^{-\tau/\theta}\right]$$

$$E = (3.94)10^8 W^{1/3}(W^{1/3}/R)^{2.08}\left[1 - e^{-2\tau/\theta}\right]$$

where I is the impulse (lb.sec/in^2)

E is the energy (ft.lb./in^2)

τ is the cut-off time (in the same units as θ)

For any underwater explosion there is always a distance from the explosion beyond which the propagation of the shock wave near the water surface ceases to obey acoustic theory and becomes anomalous. In this anomalous region the reflected wave catches up with the incident shock wave decreasing its peak pressure and lengthening its duration beyond the acoustic cut-off time. The ranges of interest to target response at Bikini BAKER were within the anomalous region, but for depths of burst greater than 200 $(W)^{1/3}$ (ft.) the pressure pulses capable of causing serious damage are unlikely to occur in the anomalous region.

The sea bed reflects the shock wave as a positive pulse but the phenomenon is complicated by the variable rigidity and lack of flatness of sea beds and the faster propagation of energy along sea bed material than in water. The importance of the sea bottom reflection is much less than that from the sea surface since the very maximum that it can do is to increase the effective charge weight by 100% (when the charge is exploded in contact with a perfectly rigid bottom). In practice, even for bursts on the bottom an enhancement of 50% is all that can be expected.

The refraction of shock waves due to sound velocity variations in oceans can lead to significant modification of the pressure pulse, compared to that in isovelocity water. The resulting pressure pulses can bear little resemblence to the original exponential form and regions of relatively low and high peak pressures are developed. The effects of refraction are of small interest for weapons of a few kilotons yield, begin to be significant at around 20KT, and are likely to be the dominating feature for megaton yields.

The fireball continues to expand after the shock wave has been generated and, provided that the depth of burst is sufficiently large, a maximum radius is reached without much vertical migration. At the maximum radius the pressure in the bubble is less than the hydrostatic pressure at the depth of its centre, and a contraction occurs. Inertia effects cause several pulsations to occur until venting at the sea surface occurs due to upward migration. Large vertical migrations occur during the periods when the bubble radius is small: for example, the upward migration at the first minimum for a 20 K.T. bomb detonated at 2,000 ft. is of the order of 300 ft. At its first minimum radius a pressure pulse is emitted which is an order of magnitude below that of the shock wave and subsequent pulses are of decreasing magnitude. The damaging power of the bubble pulses is small compared to that of the shock wave for the reasons given in Section (4.11).

Many other features of underwater nuclear explosions are associated with the bubble motion. Surface waves are formed in the process of filling in the depression created in the sea surface when the bubble vents. Water column formation is governed by the state of the bubble on venting, i.e. by whether the bubble radius is near a minimum or maximum, and cratering of the sea bottom is associated with bubble energy.

References

(1) Manual on the Effects of Atomic Weapons (Chap. 4)
A.W.R.E. (Secret/Atomic/U.K. Eyes Only)

(2) Capabilities of Atomic Weapons. A.F.S.W.P./
U.S. Dept. of the Army. Manual TM23-200
Edition of November, 1957. (Confidential)

CHAPTER 2 - THE RESPONSE OF SUBMERGED STRUCTURES

2.1. Complicating Factors

The response of submerged air-backed structures to underwater shock waves is greatly complicated by the fact that the total loading applied depends upon the response. This results from the high acoustic impedance ρc (density times sound velocity) of water of approximately 5.76 (lb. sec. in^{-3}) which is related to the pressure p and particle velocity v for waves in one dimension by the equation

$$p = \rho c v$$

For example a pressure of 1,000 p.s.i. is associated with a particle velocity of only 14 ft./sec. so that quite moderate velocities of a structure can result in significant pressure changes.

Another characteristic of underwater shock response is the small loading durations even for nuclear weapons. The time constant for the exponential decay of up to 100 K.T. bursts is less than 50 milliseconds and the effect of surface cut-off will usually keep shock wave loading durations below this value even for megaton weapons. The unimportance of bubble pulse loadings from nuclear explosions, which is explained in Section (4.11), makes the loading duration even less than for conventional high explosive attack.

2.2. Shock Wave Reflection

2.2.1. Normal Incidence on infinite air-backed plate

The most important underwater shock wave response problem is that of an infinite air-backed plate hit at normal incidence by a plane shock wave. The acoustic approximation to wave propagation can be used in solving this problem since for pressures of a few thousand p.s.i. the density changes of water and metals are very small.

When the shock wave hits the plate a compression wave of the same exponential decay but higher peak pressure propagates into the plate and a similar compression wave of lower peak pressure travels back into the water. Since this latter wave is added to the original shock wave the total pressure in the water is increased by the plate's presence. The shock wave in the plate strikes the surface in contact with air, which is effectively a free surface, and is reflected back as a rarefaction wave which then hits the water-plate interface, etc., etc. The problem of these multiple reflections is complicated but easily soluble. A simpler solution of sufficient accuracy for practical purposes can, however, be obtained by neglecting the wave motion in the plate and considering the latter as a rigid mass. This is justified by the small period of these oscillations through the thickness of the plate, compared to the decay constant of the shock wave. For obvious reasons this approximation is not valid when the response of very thick concrete walls, as used in dams, is under consideration.

Notation

m is the mass/unit area of the plate (lbs. weight/386 $in.^2$)

v is the velocity of the plate (in./sec.)

ρc is the impedance of water (lb.sec. $in.^{-3}$)

p_i is the incident pressure of the wave in the water which travels towards the plate (p.s.i.)

p_r is pressure of the reflected wave in the water which travels away from the plate (p.s.i.)

x is the distance from the plate measured into the water (in.)

t is the time measured from the instant the shock wave hits the plate (secs.)

Equating the particle velocity in the water at the plate (x = 0) and the plate velocity gives

$$(p_i - p_r)_{x=0} = \rho c v \tag{1}$$

The acceleration of the plate gives

$$(p_i + p_r)_{x=0} = m\dot{v} \tag{2}$$

Eliminating p_r between equations (1) and (2) gives the equation governing v as

$$m\dot{v} + \rho c v = (2p_i)_{x=0} = 2P_m\, e^{-\frac{t}{\theta}} \text{ say} \tag{3}$$

Solving with v = 0 at t = 0 gives

$$\text{Plate velocity } v = \frac{2P_m}{\rho c(z-1)}\left[e^{-(t/z\theta)} - e^{-(t/\theta)}\right] \tag{4}$$

$$\text{Reflection pressure } p_r = P_m\left[\left(\frac{z+1}{z-1}\right)e^{-(ct-x)/\theta c} - \left(\frac{2}{z-1}\right)e^{-(ct-x)/\theta zc}\right]_{(x<ct)} \tag{5}$$

$$\text{Total pressure } p_i + p_r = P_m\left[\left(\frac{z+1}{z-1}\right)e^{-(ct-x)/\theta c} - \left(\frac{2}{z-1}\right)e^{-(ct-x)/\theta zc} + e^{-(ct+x)/\theta c}\right]_{(x<ct)} \tag{6}$$

where $z = \dfrac{m}{\rho c\theta}$

Particular results of interest are as follows:-

$$\text{Maximum plate velocity } V_{max} = \left(\frac{2P_m}{\rho c}\right) z^{z/(1-z)} \tag{7}$$

$$\text{Time to maximum plate velocity } t_{v_{max}} = \frac{\theta z}{(z-1)} \log_e n \tag{8}$$

Time to zero reflection pressure $$t_{(p_r = 0)} = \frac{\theta z}{(1 - z)} \ln \left(\frac{2}{1 + z}\right) \quad (9)$$

The reflected pressure p_r is instantaneously equal to the incident peak pressure at $t = 0$ but decreases rapidly to negative values until it finally cancels the incident pressure. At this time the plate reaches its maximum velocity since $p_i + p_r$ becomes negative. The maximum velocity and time to maximum velocity are of considerable importance in target response and are plotted as functions of z, P_m and θ in Figure 1. With the plate thickness h in inches and θ in milliseconds the expression for z becomes

$$z = \frac{h}{(7.6)\theta} \text{ for steel plates} \quad (10)$$

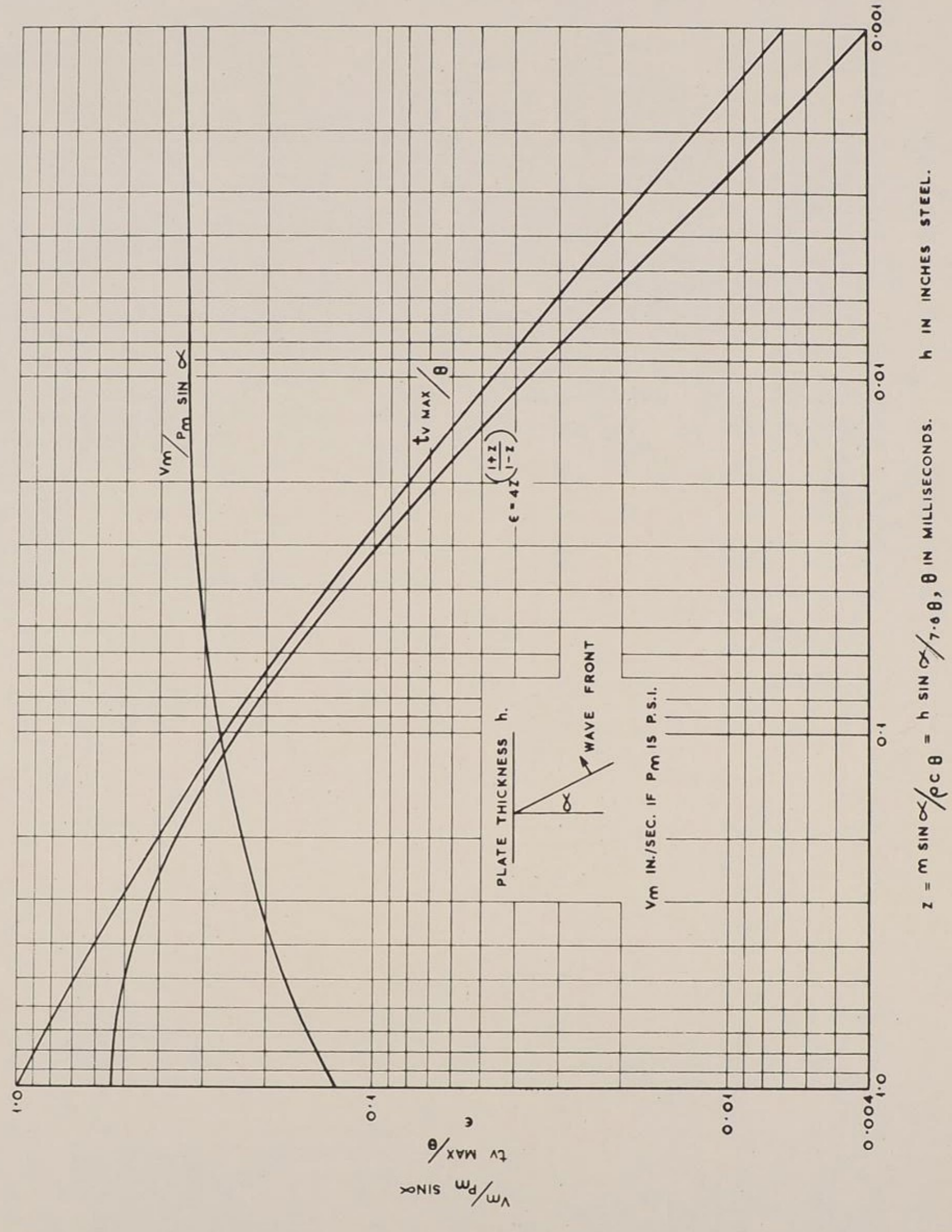
For times greater than $t_{v_{max}}$ cavitation effects predominate and the above treatment breaks down.

2.2.2. Oblique incidence on infinite air-backed plate

The case of an infinite air backed plate hit obliquely by an infinite plane shock wave is also of interest, and can be treated approximately by a simple modification of the case of normal incidence. Strictly, of course, the unequal motion of a plate hit obliquely causes an elastic or plastic bending wave to run along the plate ahead of the shock wave, generating a precursor wave of pressure in the water. This effect is observable but is usually of little importance, and it is convenient to assume that the plate is infinitely flexible so that elastic effects are absent and the elements of the plate move independently. Then, neglecting diffraction effects, the solution for normal incidence holds if ρc is replaced in all formulae by $\rho c/\sin\alpha$, where α is the angle that the shock wave front makes with the normal to the plate. The solution breaks down for nearly glancing angles (say $\alpha < 15^{\circ}$) when diffraction effects become predominant. For completely glancing angles ($\alpha = 0$) the solution gives zero motion for the plate, which implies a pressure loading acting on the plate which is equal to the incident pressure pulse. Clearly zero motion and finite applied pressure are mutually incompatible.

2.2.3. Water backed plates

Water backed plates occur in naval structures, for example in side protection systems, and their response to shock waves is easily obtained from the solution for an air backed plate by writing $2\rho c$ for ρc. This is because the hydrodynamic damping is applied on both sides of the plate. It must be noted, however, that negative pressures can never be generated in this case so that cavitation cannot occur. In consequence damage to water backed plates is much less than that to air backed plates.



THE RESPONSE OF AIR-BACKED PLATES

2.3. The Effect of Cavitation

The critical tension for the inception of cavitation in sea water during the short time of action of a shock wave is not accurately known. Some evidence is available to show that the critical tension is less than 50 p.s.i. for the pulses from quite small high explosive charges. For the much longer duration pulses for nuclear explosions the critical tension would be lower and can probably be assumed equal to zero. On this assumption, for reasons given below, cavitation occurs at an air backed plate when the maximum velocity v_{max} is reached, the kinetic energy per unit area of the plate then being $(\frac{1}{2})\ m\ v^2_{max}$. At least this amount of energy is available for causing damage and the ratio of this maximum kinetic energy of the plate to the incident shock wave energy is given by the factor.

$$\frac{4z^{(1+z)/(1-z)}}{1-e^{(-2\tau/\theta)}}$$

The factor outside the brackets is plotted as ε in Figure (1) Section 2.2.

Strictly the theory only applies to an infinite air backed plate but simple arguments show that actual ship's plating would respond in a similar manner. At the time at which v_{max} occurs the displacement normal to the plate is so small that the pressure required to cause it would be small.

It is assumed above that for zero critical tension the hydrostatic pressure can be neglected and that the water first cavitates at the plate. This assumes that the sum of incident plus reflected pressure waves first becomes zero at the plate and it is not immediately obvious that this will always be the case. The pressure distribution at the instant of maximum plate velocity for a particular example is shown in Figure (1). The total pressure is seen to be zero only at the plate, and at all earlier times the total pressure must have been everywhere positive; thus cavitation first occurs at the plate in this case. This is probably always true for response to nuclear explosions since the incident pressure decays little in the time to cavitation and the reflected wave goes from positive to negative in this time.

It is clear that the occurrence of cavitation has the effect of increasing the damage to air backed structure. This is because cavitation cannot occur until the total pressure is negative (or zero), after which time the structure would be retarded by the tensions present in the water if cavitation did not occur. There are reasons for believing that cavitation enables most of the incident shock wave energy to do damage. For example, assuming a zero cavitation tension, the shock wave energy can only be reflected by compression waves. Thus apart from the very small amount of energy in the initial short duration compression wave that is reflected from the plate, most of the energy is directed towards the plate. Some of this energy is lost in inelastic collisions as the spray thrown across the cavitation gap collides with the water that has already coalesced with the plate.

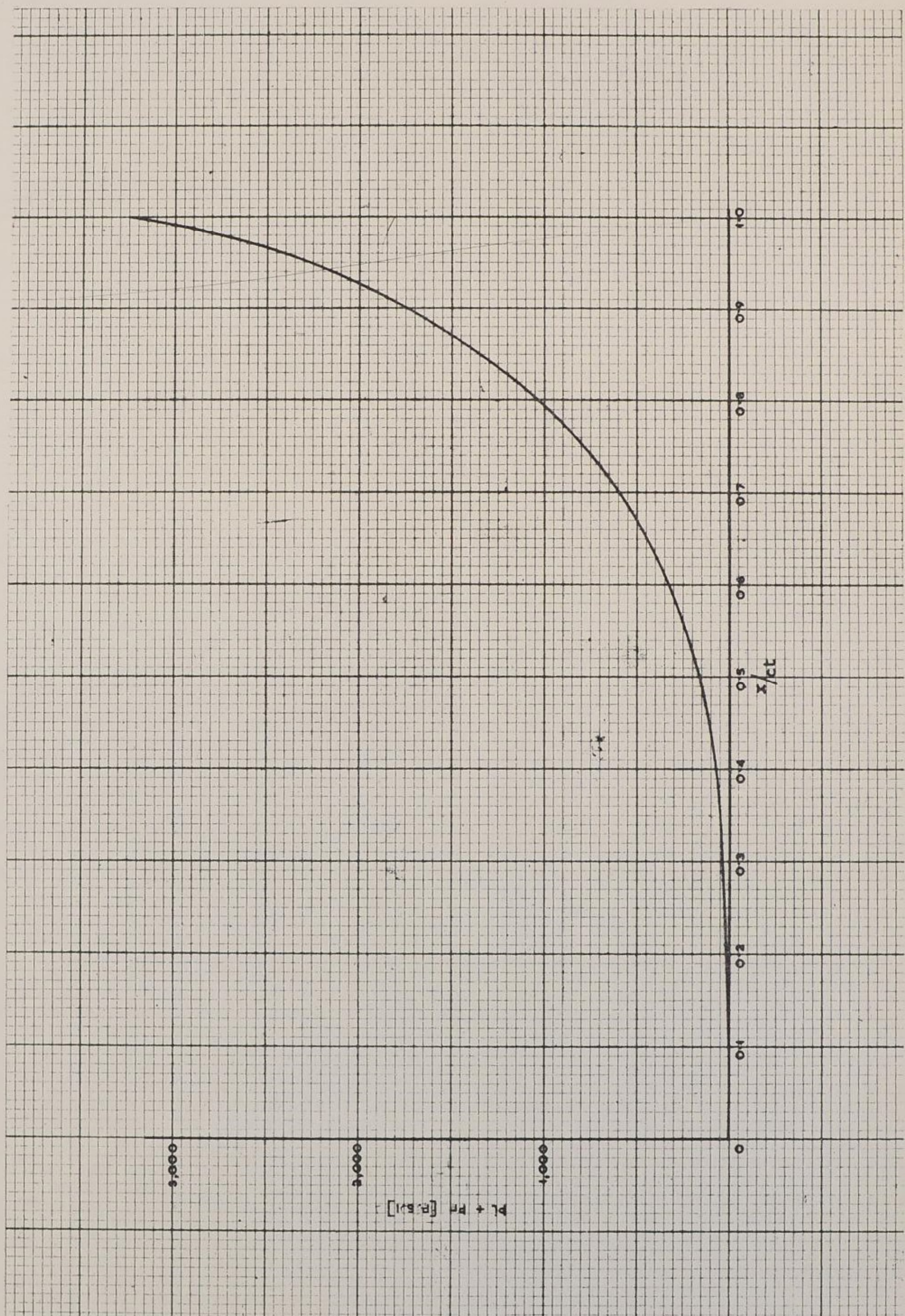
Theoretical work by Temperley (1) has shown that about two thirds of the shock wave energy can be expected to be absorbed by the plating, most of the remainder being lost by inelastic collisions. Experimental work at U.E.R.D. (2), however, has indicated that this spray reloading may not be as important as theory suggests. There is a considerable need for more experimental information on this subject.

At first sight the effect of cavitation will only be to increase the proportion of the shock wave energy prior to cut-off that gets on to the plate. However cut-off due to reflection at the free surface is also accompanied by cavitation and this may result in ships bottom structure absorbing more than just the energy prior to cut-off. This question is discussed in more detail in Section (3.4).

References:

1. Underwater Explosion Research Vol. III - "The Damage Process" O.N.R. "Theoretical Investigation of Cavitation Phenomena occurring when an Underwater Pressure Pulse is Incident on a Yielding Surface: I".

2. Underwater Explosions Research Division, Norfolk Naval Shipyard Report 17 - 49 "Afterflow and Reloading". (CONFIDENTIAL.)



PRESSURE DISTRIBUTION AT TIME OF
MAXIMUM VELOCITY

CHAPTER 3 - DAMAGE MECHANISMS FOR SURFACE SHIPS

3.1 The Types of Damage

The damage to surface ships caused by underwater explosions from conventional and atomic weapons falls into two fairly distinct types. Firstly, the general shaking up of the surface ship caused by the shock wave can cause machinery to be displaced or damaged so as to impair the operation of the ship or even, in severe cases, to cause loss of mobility. This type of damage is generally referred to as shock damage, and can be reduced by the improved design of machinery and mountings. For more severe shock wave loadings hull rupture will occur. The problem of hull rupture will be considered first.

3.2 The Mechanism of Hull Splitting

Less is known about the problem of hull splitting in surface ships than about submarine lethality, even although one very costly full scale trial involving surface ships has been held (Bikini BAKER). The lack of knowledge may be attributed to the following causes:-

(a) Much less work has been carried out on model scale, partly because realistic surface ship models are very difficult to make;

(b) The effect of surface cut-off can be expected to dominate the response mechanism;

(c) Cavitation effects can be expected and these considerably complicate the hydrodynamics;

(d) For shallow bursts the tension wave reflected from the sea surface propagates anomalously.

The Bikini BAKER trial was carried out in shallow water (180 ft. depth) with a shallow bomb (90 ft. depth of burst), so that anomalous propagation and bottom reflections could be expected to modify the pressure pulse signature very considerably. However, some sort of agreement was found with a simple theory suggested by Sir William Penney (1), and this will now be described.

3.3 "Energy To Time of Cut-Off" Criterion

This simple theory assumes that damage is governed by the energy in the shock wave pulse up to the time of cut-off. To a reasonable approximation this energy can be written -

$$E_\tau = P_m^{\,2}\tau/\rho c \qquad (1)$$

in the region where linear surface reflection applies.

where P_m is the peak shock wave pressure
ρc is the acoustic impedance of water
τ is the cut-off time.

In the region of anomalous surface reflection the peak pressure is reduced

and the duration is lengthened relative to the values in the linear reflection region and the more general expression -

$$E_\tau = \frac{1}{\rho c} \int_0^\tau p^2 dt \qquad (2)$$

must be used where p is the pressure at time t after the arrival of the shock wave. An analysis of Bikini BAKER data suggested the following:

Table 1 : Critical Values of E_τ

(1) Any capital ship will be sunk by a value $E_\tau = 10^5$ ft. lb./ft.^{2}.

(2) Any capital ship will be seriously damaged by $E_\tau = 5.10^4$ ft. lb./ft.^{2} but will not sink from rupture of plates. Some danger of sinking will arise from fractured pipes.

(3) Lighter ships such as destroyers transports and merchant ships will probably be sunk by $E_\tau = 2.10^4$ ft. lb./ft.^{2}.

(4) Submarines will probably be sunk by $E_\tau = 10^4$ unless leaks not through the main pressure hull but through hatches and fractured pipes can be stopped.

The point was made that for glancing or near glancing angle attack only half of the energy to time of cut-off should be taken. This is because the kinetic energy which constitutes half the total energy in a one dimensional wave is associated with particle velocities parallel to the ship's bottom for glancing angles and is unlikely to cause damage. Since the critical values of E_τ listed above were derived from a glancing angle trial the values for more normal incidence attack should presumably be halved on this argument.

To a good approximation the cut-off time τ can be written

$\tau = 2Dd/Rc$ (secs.) where

D is the depth of burst (ft.)

d is the depth of the point under consideration (ft.) (the draught of the ship).

R is the slant radius from the charge (ft.)

c is the velocity of sound in water (ft./sec.)

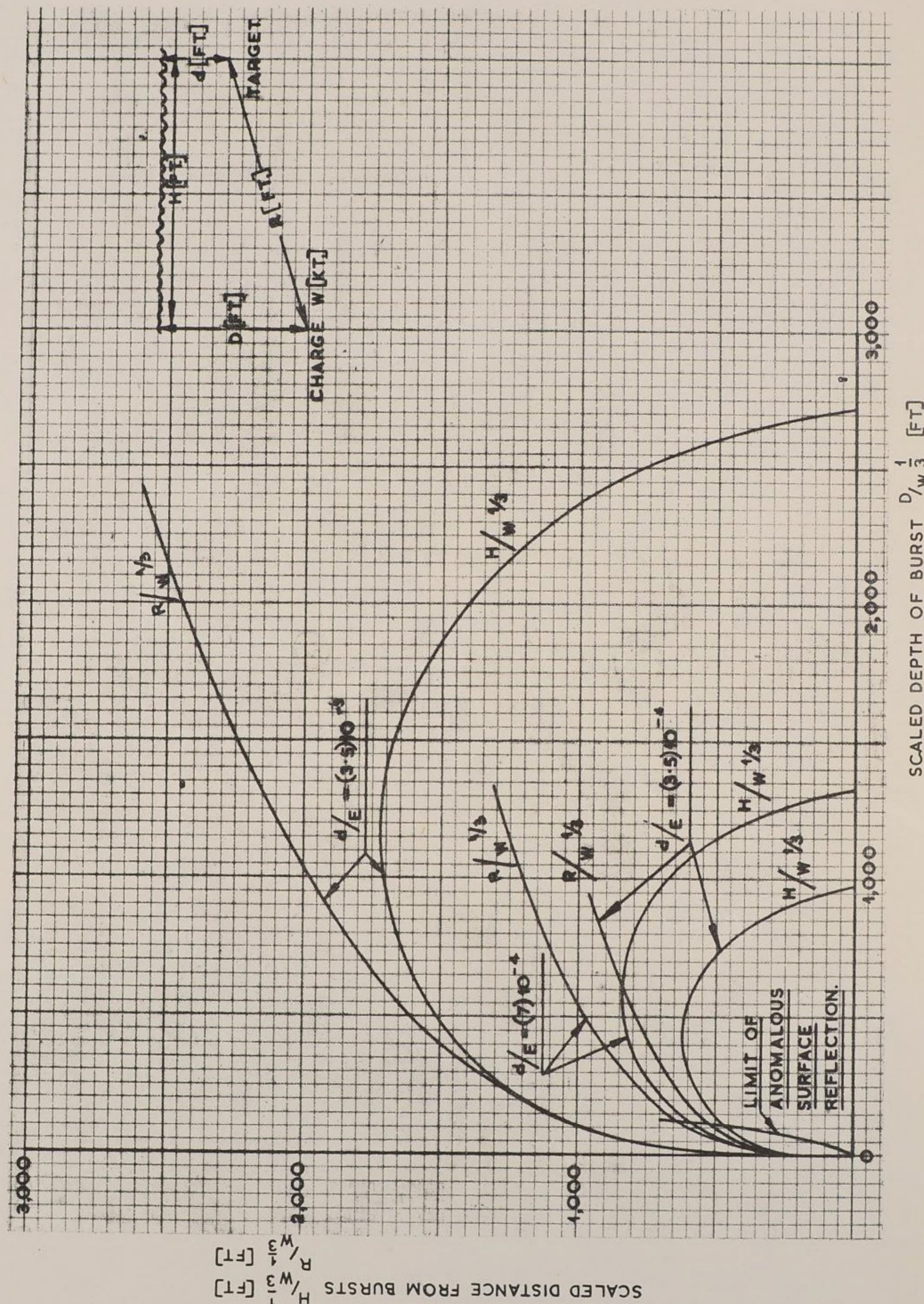
This leads to -

$$E_\tau = \frac{2DdP_m^2}{R\rho c^2} \qquad (3)$$

showing that the slant radius R is a function of (E_τ/d) and D the depth of burst. Curves of slant range $R/(W)^{1/3}$ and horizontal range $H/(W)^{1/3}$ against $D/(W)^{1/3}$ are given in figure (1) for several values of E/d. Also shown in figure (1) is a plot of the horizontal range beyond which the surface reflection is anomalous. The curves of $H/(W)^{1/3}$ and $R/(W)^{1/3}$ do not strictly hold to the left of this anomalous propagation curve since energy is reduced in the anomalous zone.

The energy required to rupture the plating of large ships will obviously be greater than that required to rupture the plating of small ships and it is reasonable to assume that the ratio (energy required to rupture/draught) will be reasonably constant. This leads to the result that using this criterion all classes of ships will receive roughly similar damage at the same range.

For References, see end of Chapter.



UNDERWATER DISTRIBUTION OF
SHOCK ENERGY

3.4 An Alternative Energy Criterion

The assumption that damage is proportional to the energy in the shock wave up to the time of cut-off is open to at least one serious objection. This is that, although the arrival of the wave reflected from the free surface reduces the pressure to nearly zero, the particle velocity may be increased or decreased by its arrival. For example for a point near the surface and directly above the explosion the particle velocity (vertical) is doubled by the reflected wave. For points near the surface at large horizontal distances the resultant particle velocity (nearly horizontal) is reduced almost to zero by the reflected wave.

In the cases where the vertical particle velocity is increased at cut-off it is difficult to see why only the energy prior to cut-off is available to cause damage. There is little doubt that the shock wave kinetic energy can be as damaging as the shock wave potential energy and the effect of cut-off is roughly speaking to convert some of the potential energy into vertical kinetic energy. The following argument makes clear that energy prior to cut-off cannot be a universal damaging criterion.

Consider what happens as the draught of a given ship under attack from a given weapon at a given range and depth is continuously decreased to zero (how this could be achieved in practice is left open to conjecture). The energy prior to cut-off continuously reduces until at zero draught it is zero. Thus no damage will result according to the energy prior to cut-off criterion. However in the absence of cavitation and anomalous propagation the sea surface will be displaced vertically by the shock wave by a distance $x_V = \frac{2P_m\theta}{\rho c} \sin\alpha$ where α is the angle that the shock wave front makes with the vertical. For a 20 K.T. burst at 3,000 ft. θ is about 25 m sec.$^{-1}$ and x_V may be written -

$$x_V = (8.7)\ P_m \sin\alpha \text{ inches}$$

where P_m is measured in 10^2 p.s.i. The effect of cavitation would be to increase this vertical displacement. Quite clearly since peak pressures of several thousand p.s.i. are common at ranges of interest the vertical displacement of the free water surface can be well over one foot. Such displacements clearly cannot occur without seriously damaging the bottom of the ship that is hypothetically held in the free surface. This admittedly unrealistic example makes clear the dangers of ignoring the particle velocities.

The shortcomings of the criterion "energy prior to cut-off" have been demonstrated and it is necessary to consider how these can be overcome. It seems reasonable that any criterion should satisfy the following conditions:-

(a) For near glancing angle attack the criterion should for bottom damage reduce to the potential energy prior to cut-off. For this case the effect of cut-off is to reduce both pressure and particle velocities to zero. The particle velocity is in any case predominantly horizontal and is unlikely to cause bottom damage.

(b) For normal incidence attack the criterion for bottom damage should reduce to the total energy in the wave neglecting cut-off. As discussed in Chapter 2 the effect of cavitation can be expected to allow nearly all of the available potential and kinetic energy to do damage.

(c) For near glancing angle attack the criterion for side damage should reduce to the total energy prior to cut-off. The effect of cut-off will be to reduce pressure and horizontal particle velocity to zero.

These conditions are satisfied by assuming that damage is related to the values of the following quantities -

$$E_V = \left[E_p\right]_o^{\tau} + \left[E_p\right]_{\tau}^{\infty} \sin^2\alpha + E_d \text{ for bottom damage} \tag{4}$$

$$E_H = \left[E_p\right]_o^{\tau} + \left[E_h\right]_o^{\tau} \text{ for side damage} \tag{5}$$

where $\left[E_p\right]_o^{\tau}$ is the potential energy of the incident wave prior to cut-off

$\left[E_p\right]_{\tau}^{\infty}$ is the potential energy of the incident wave which is destroyed by cut-off.

E_d is the total kinetic energy of the incident wave associated with vertical particle velocities.

$\left[E_h\right]_o^{\tau}$ is the kinetic energy of the incident wave prior to cut-off, associated with horizontal particle velocities.

The damage parameters E_v and E_H may be written -

$$E_V = (P_m^2\theta/4\rho c)\left\{1 - e^{-2\tau/\theta} + \sin^2\alpha\,(1 + e^{-2\tau/\theta}\right\} \tag{6}$$

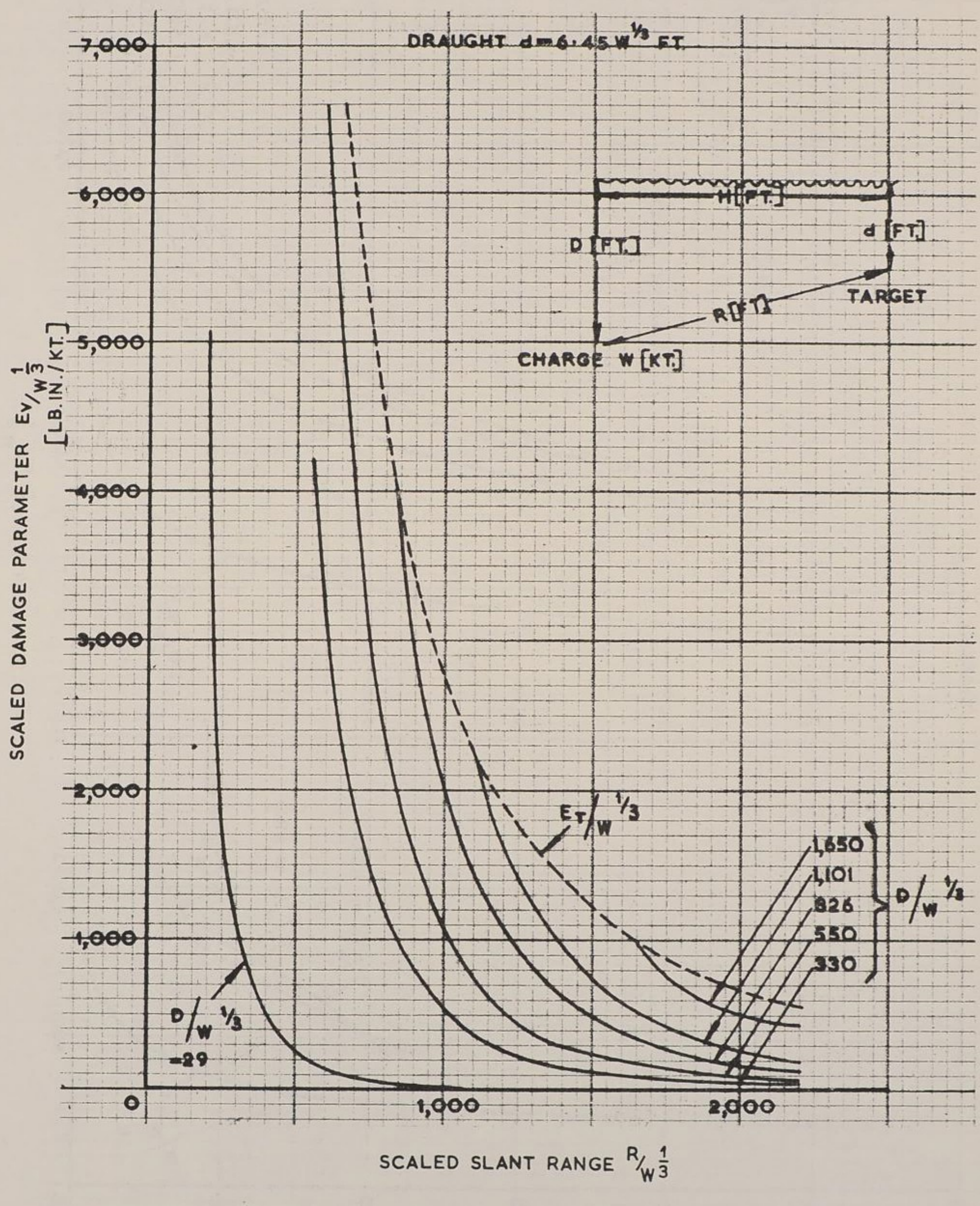
$$E_H = (P_m^2\theta/4\rho c)\left(1 - e^{-2\tau/\theta}\right)(1 + \cos^2\alpha) \tag{7}$$

The expression for E_V assumes that the potential energy which can be converted to vertical kinetic energy by the wave reflected from the free surface is only $\sin^2\alpha$ times the potential energy destroyed by cut-off. This seems reasonable since the vertical particle velocity at the free surface associated with the reduction in pressure is $\frac{P_m}{\rho c}\sin\alpha$.

The expressions for E_v and E_h are not so convenient for plotting non-dimensionally as is equation (3) since the energies are not linear in the draught d. For this reason curves have been evaluated for only three cases of particular interest namely when $d/W^{1/3}$ = 11.0, 6.45 and 1.75. For W = 30 K.T., the first two cases reduce to d = 34.2 ft. and d = 20 ft. respectively which are possible draughts for a large aircraft carrier and a cruiser respectively. For W = 1500, the last case reduces to d = 20 ft. Curves of $E_v/W^{1/3}$ and $E_H/W^{1/3}$ against $R/W^{1/3}D/W^{1/3}$ for these three values of d are given in figures (1) - (6). Curves of R and H against D for three values of E_v, two values of d and W = 30 are given in figures (7) and (8). Similar curves for d = 20 and W = 1500 are given in figure (9). Since the three values of E_v/d are the same in figures (7) and (8) a direct comparison of the values of R and H is of interest. It can be seen that the values of

R agree to within 10 - 15% but the values of H differ by about 20% at their maxima. The values of D at which H = 0, which gives the lethal standoff when the ship is vertically above the charge, differ by 30%. This makes it clear that using E_v as the criterion, damage ranges are not constant for constant values of E/d as they would by using E as the criterion (Section 3.3).

For References, see end of Chapter.



ENERGY PARAMETER (E_V) FOR SHIP BOTTOM DAMAGE, DRAUGHT 6·45 $W^{\frac{1}{3}}$ FT

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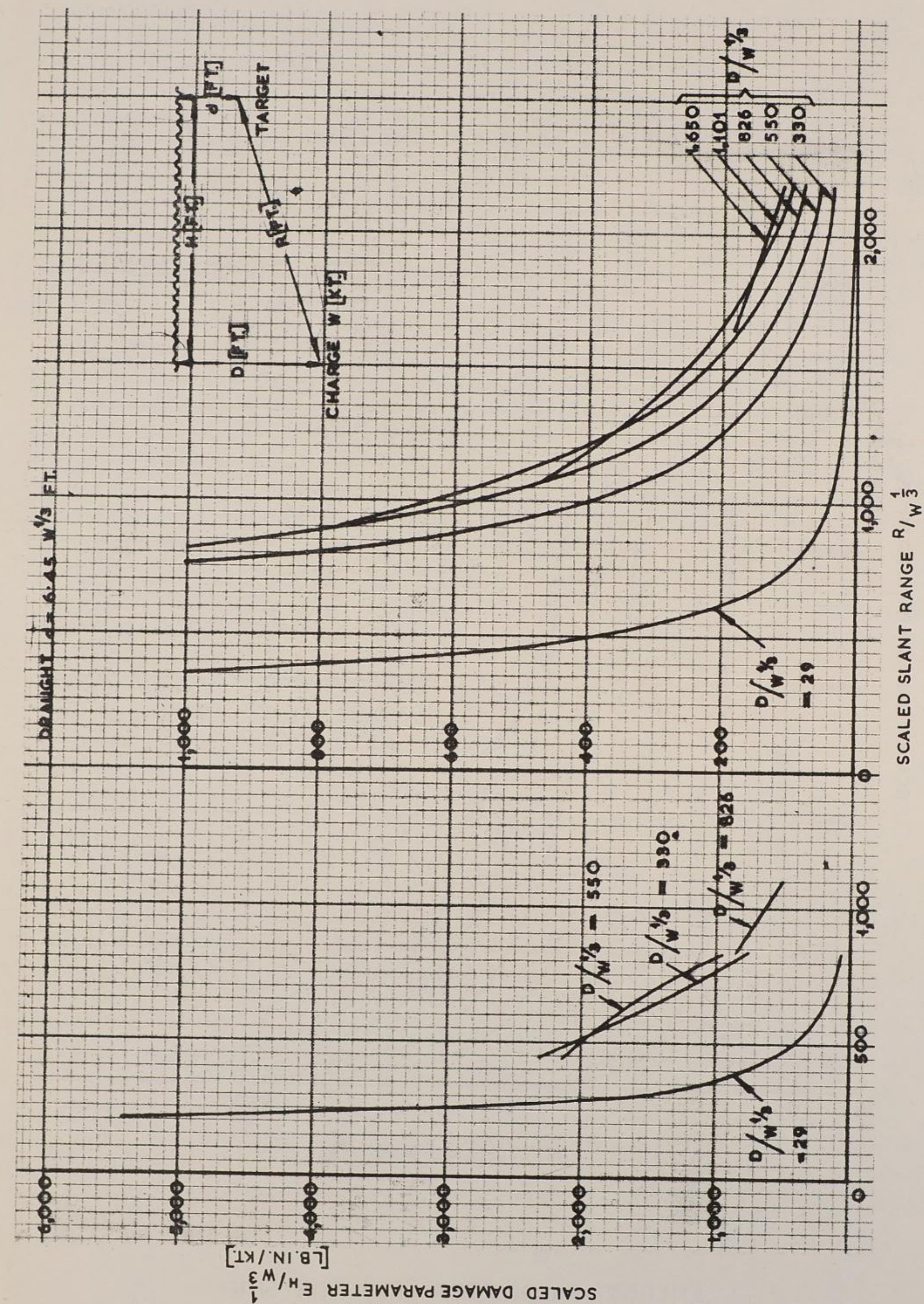

ENERGY PARAMETER (E_H) FOR SHIP SIDE DAMAGE, DRAUGHT 6.45 $W^{\frac{1}{3}}$ FT.

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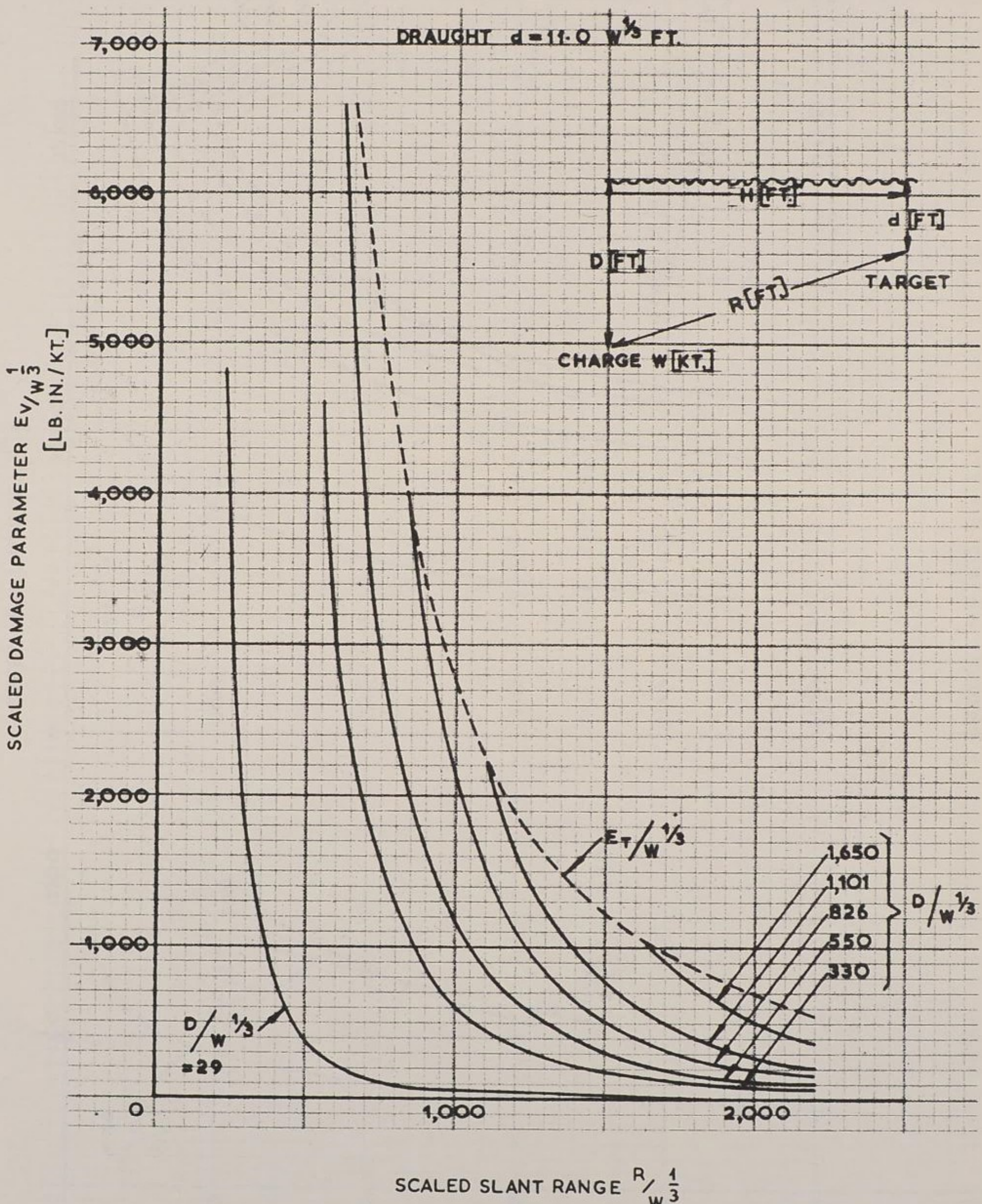

ENERGY PARAMETER $[E_V]$ FOR SHIP BOTTOM DAMAGE, DRAUGHT $11 \cdot 0\, W^{\frac{1}{3}}$ FT.

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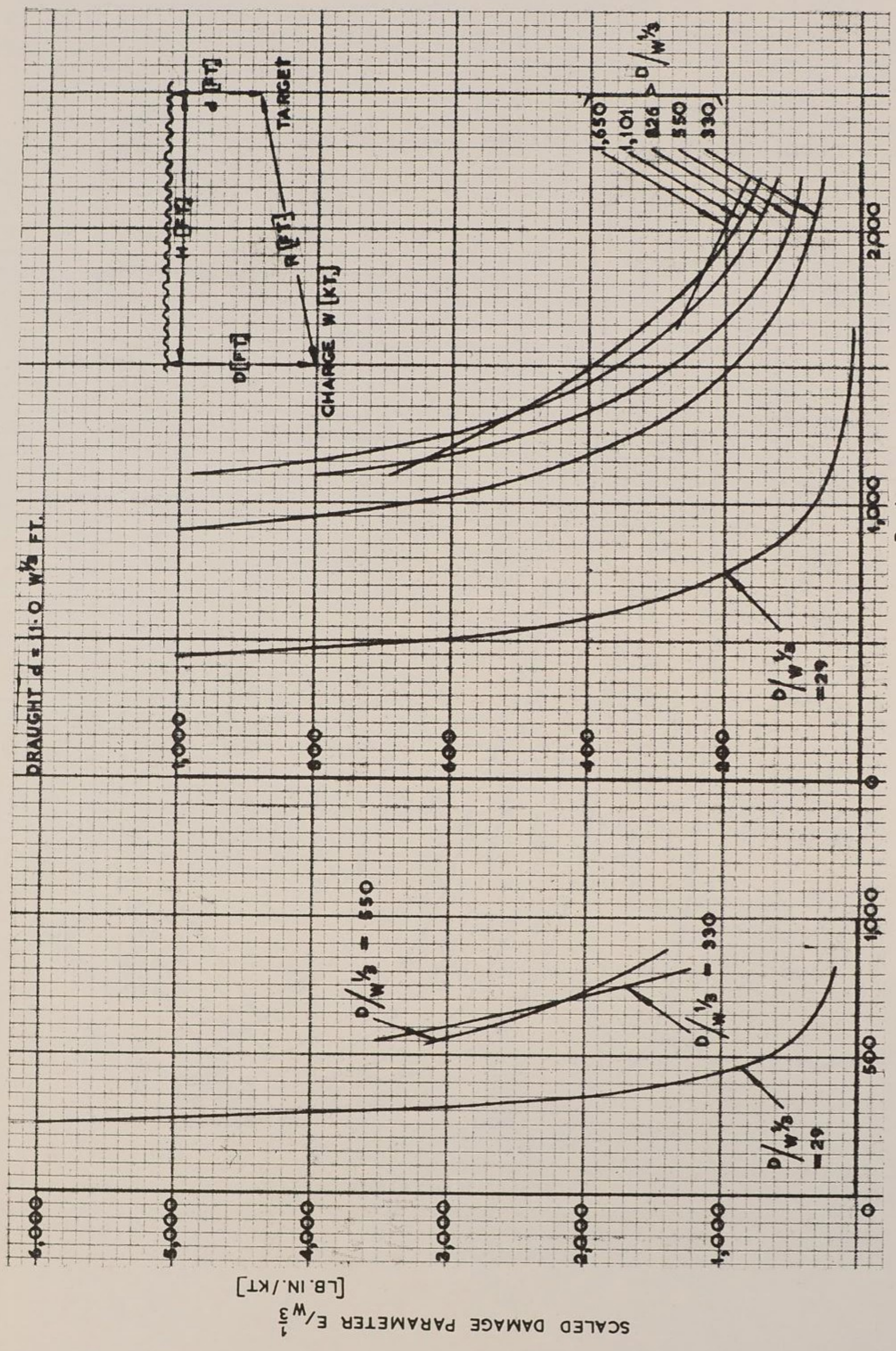

ENERGY PARAMETER (E_H) FOR SHIP SIDE DAMAGE, DRAUGHT 11·0 $W^{\frac{1}{3}}$ FT

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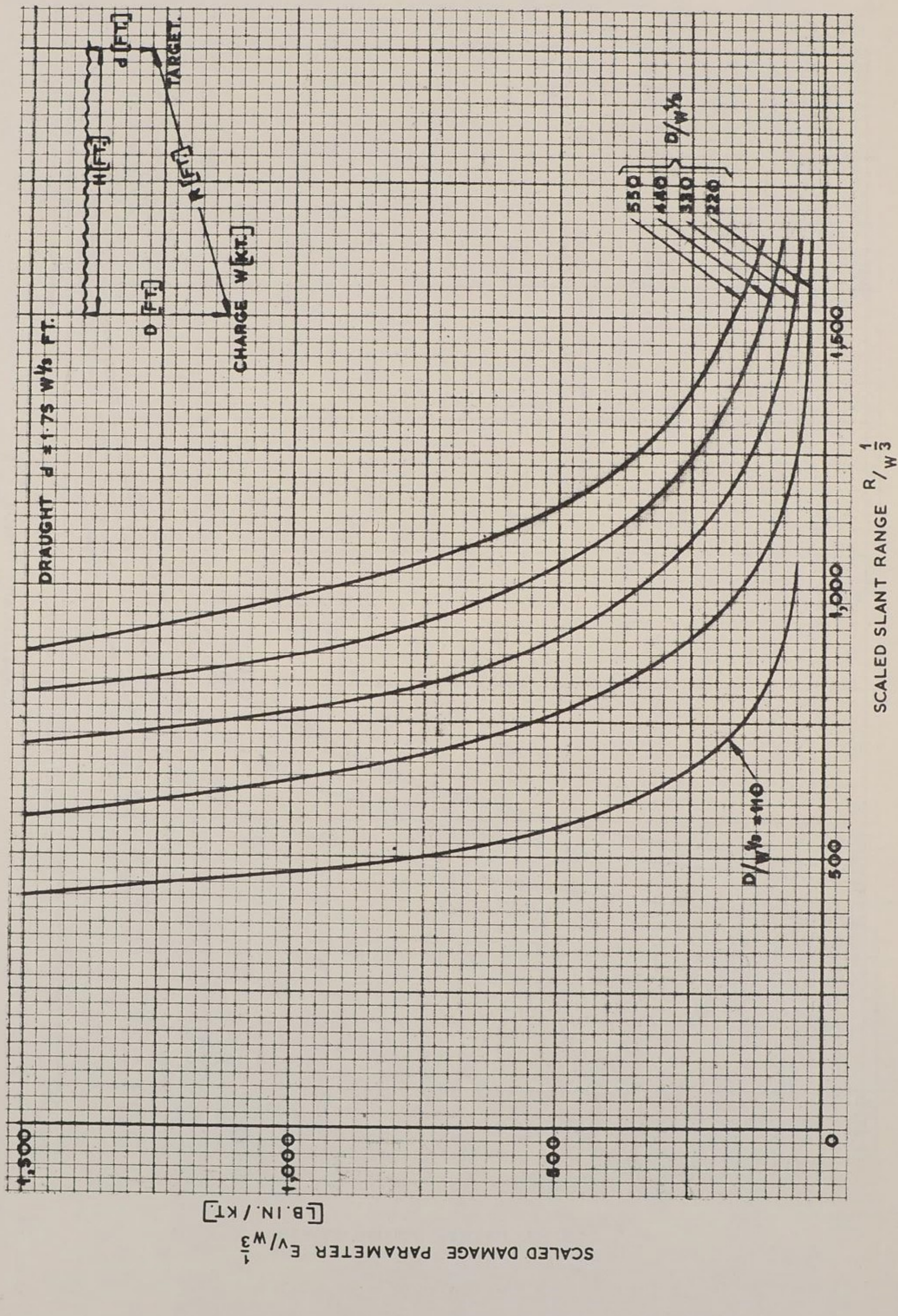

ENERGY PARAMETER (E_V) FOR SHIP BOTTOM DAMAGE, DRAUGHT 1·75 $W^{\frac{1}{3}}$ FT.

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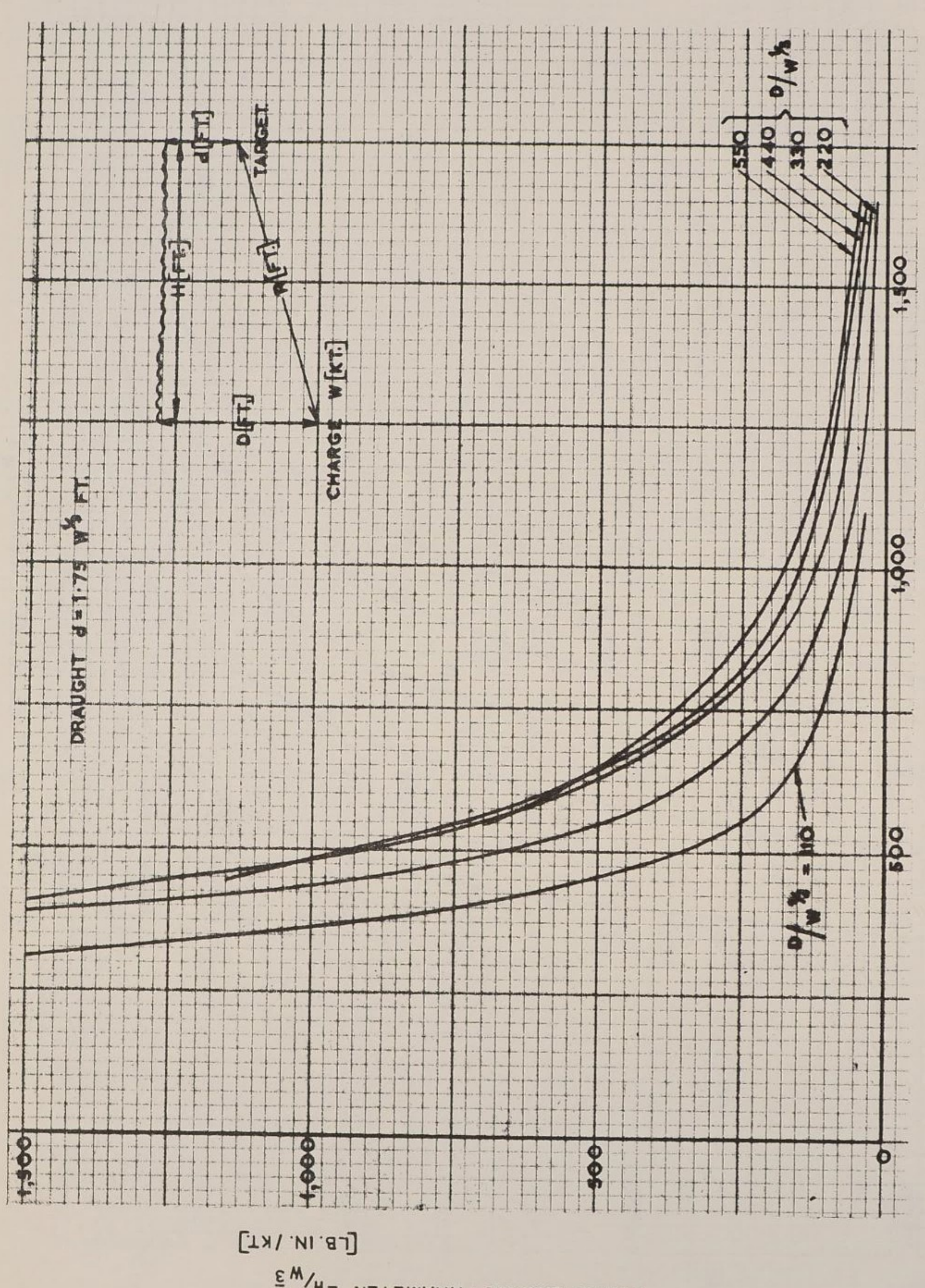

ENERGY PARAMETER (E_H) FOR SHIP SIDE DAMAGE, DRAUGHT $1{\cdot}75\,W^{\frac{1}{3}}$ FT

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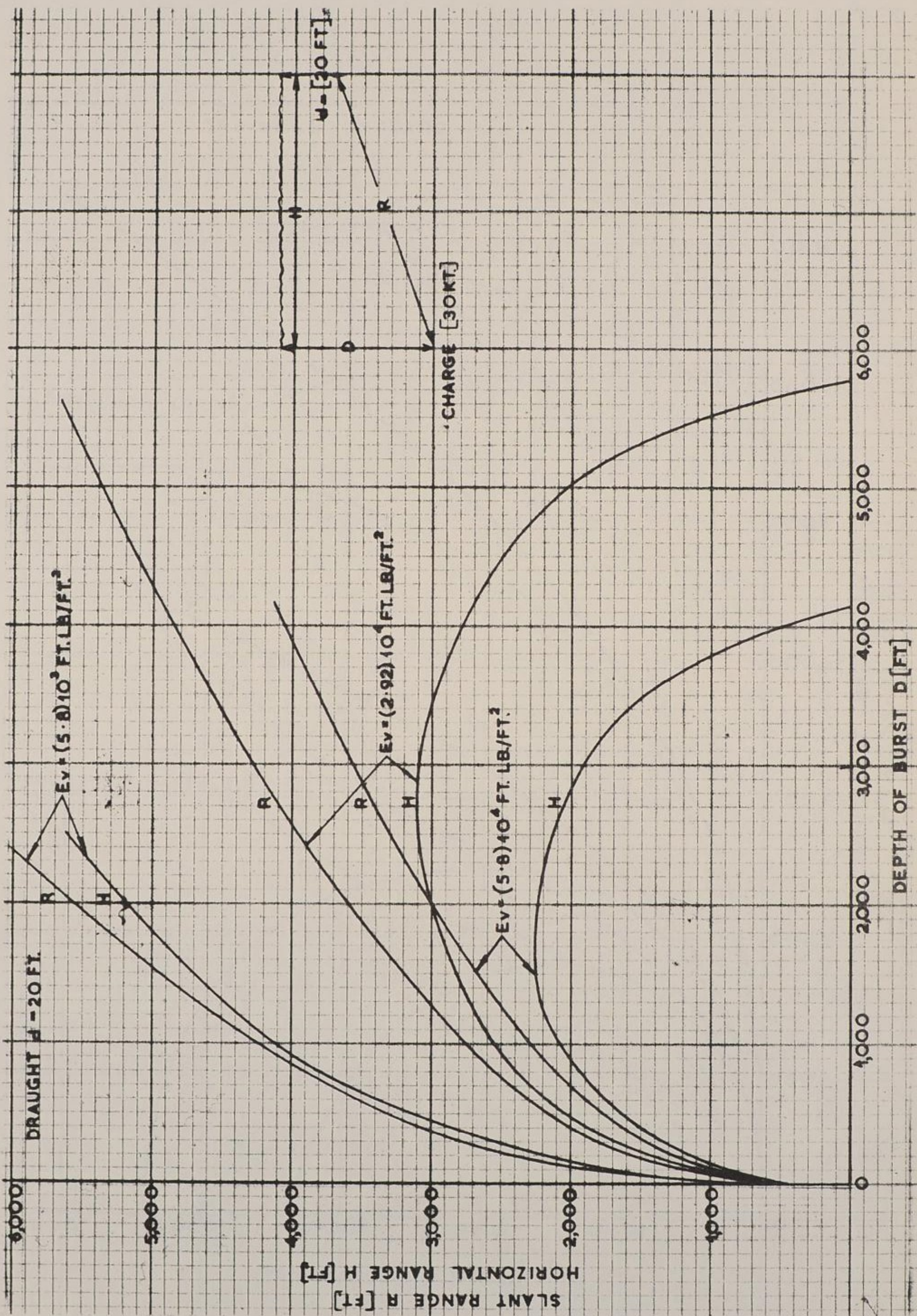

20 FT DRAUGHT SHIP, BOTTOM DAMAGE
RANGES; ENERGY CRITERION (Ev) 30 KT BURST

PART V
CHAPTER 3
SECTION 3.4
FIGURE 8

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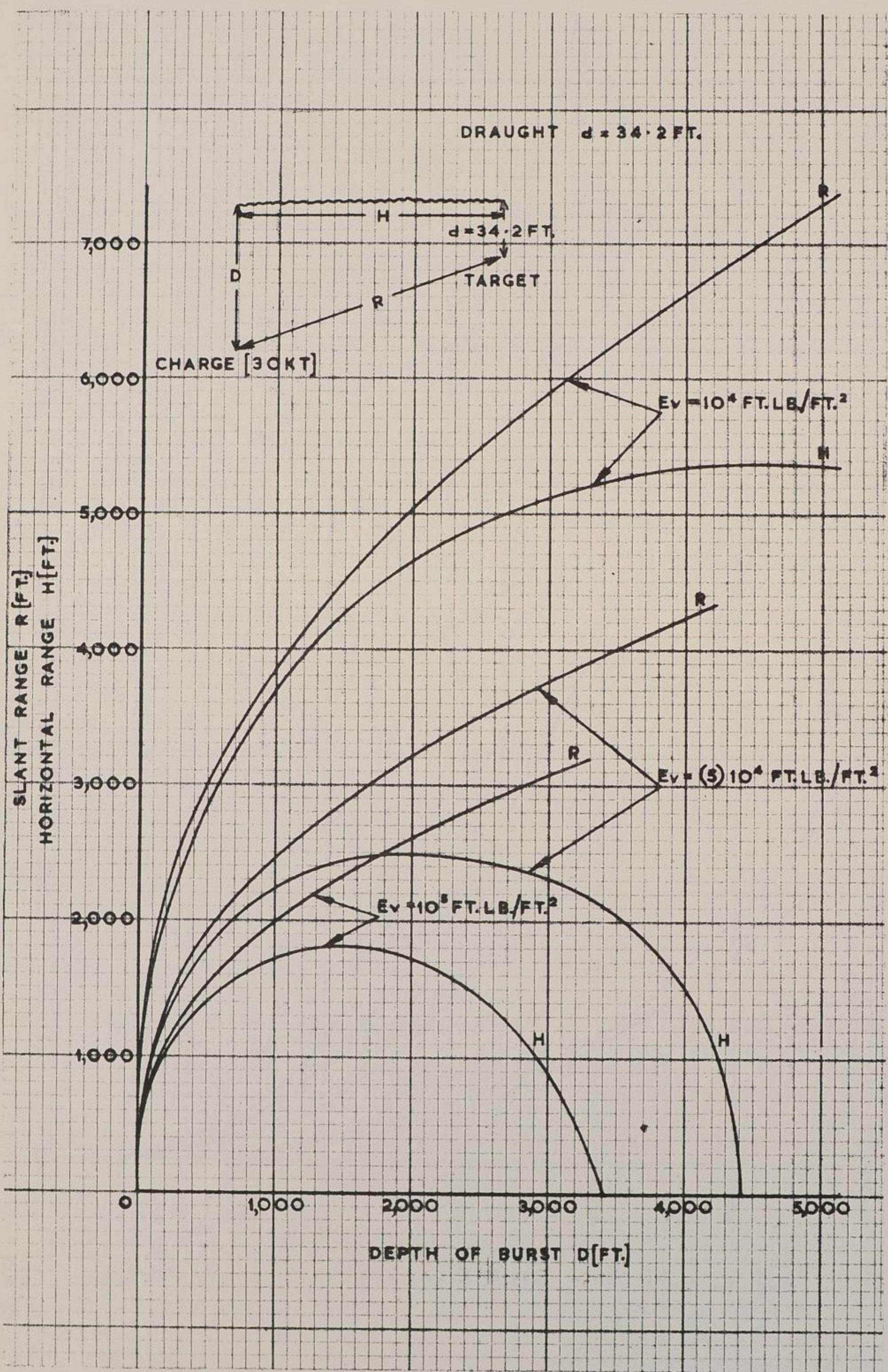

34·2 FT. DRAUGHT SHIP, BOTTOM DAMAGE RANGES;
ENERGY CRITERION (E_V) 30KT BURST

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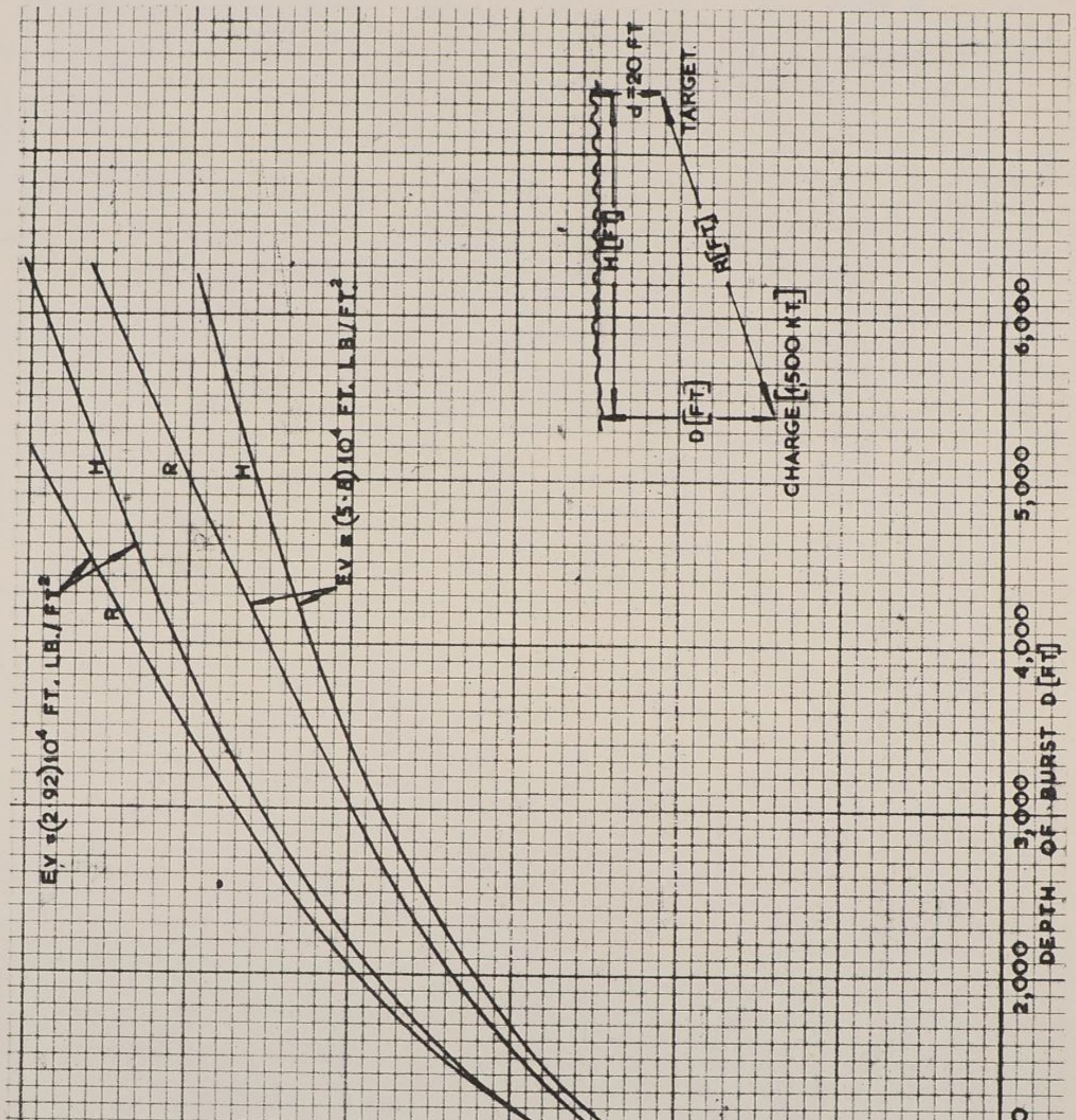


20 FT. DRAUGHT SHIP, BOTTOM DAMAGE RANGES;
ENERGY CRITERION (E_V). 1·5 MT BURST

3.5 Maximum Velocity Criterion

A third possible criterion of hull damage (the one used in Capabilities (3)) is the maximum velocity acquired in the early phase of the interaction between the shock wave and the ship's hull. This maximum velocity can be readily evaluated using the velocity curve given in figure (1) (Section 2.2) and in most if not all cases of interest, for charges greater than 1 K.T., the velocities reduce to the simple form -

$$\text{maximum horizontal velocity } V_h = 2P_m \cos\alpha/\rho c \qquad (8)$$

$$\text{maximum vertical velocity } V_v = 2P_m \sin\alpha/\rho c \qquad (9)$$

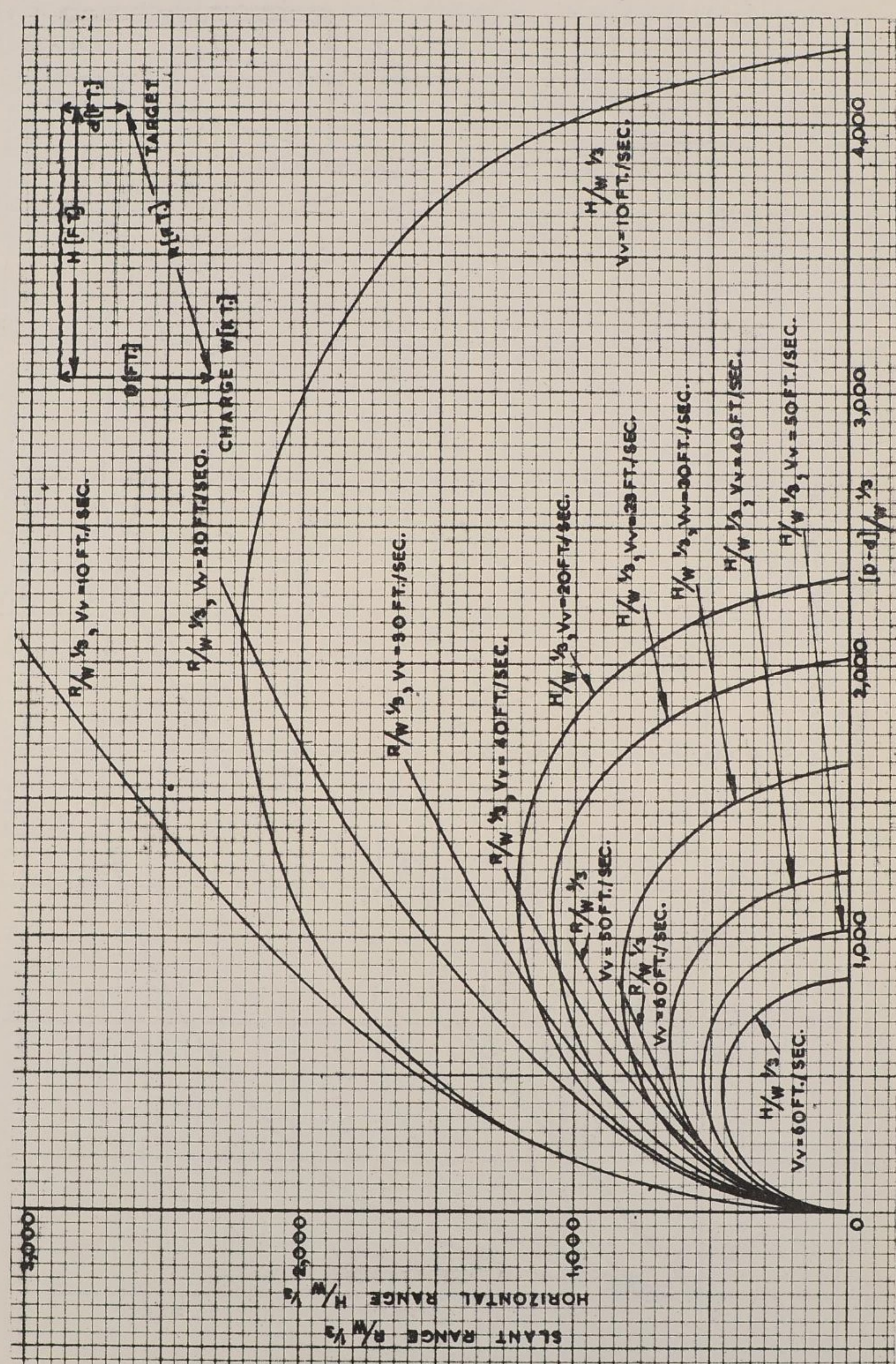
The cut-off time can be expected to be too long to affect these maximum velocities in all cases of interest.

Curves of $R/W^{1/3}$ and $H/W^{1/3}$ against $(D-d)W^{1/3}$ for several values of V_v and V_H are given in figures (1) (2).

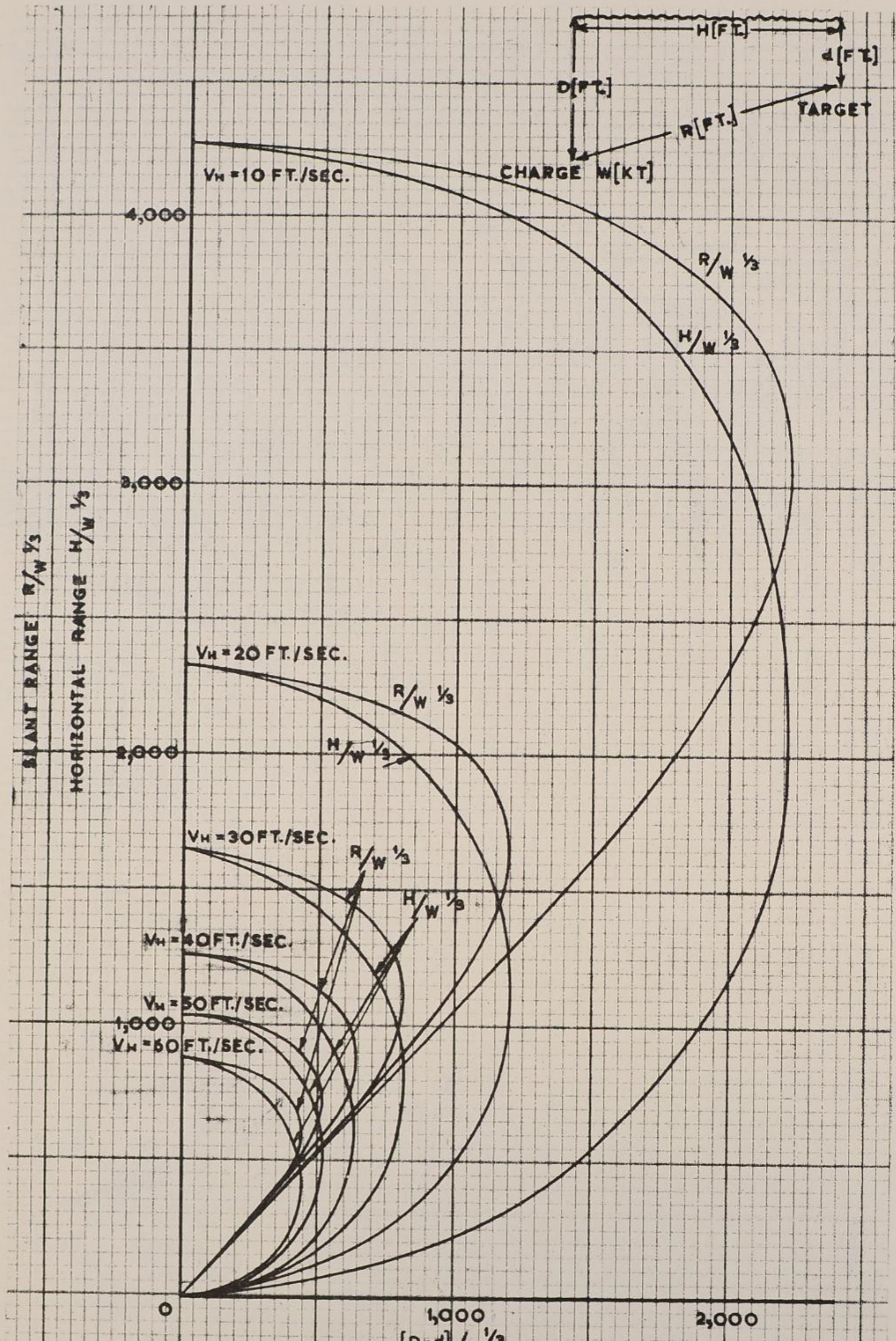
The values of V_v and V_h to be taken for hull splitting are not certain. Capabilities (3) appears to use a value of about 30 ft./sec. for V_v for Transports, Aircraft Carriers and Cruisers and about 24 ft./sec. for Destroyers and Landing Craft. A considerably higher value of V_h is likely to be necessary to cause hull splitting since the mass and hence the energy associated with the velocity is much smaller. A value of 70 or 80 ft./sec. would lead to similar energies and is implied in reference (2) page 263. No value is given in Capabilities (3).

The use of the maximum velocity as a criterion of hull damage is tantamount to using the maximum kinetic energy transmitted to the hull as a critical parameter. The value of this maximum kinetic energy assumed is usually quite small. For example with an average bottom weight/unit area of 200 lb./ft.^{2} and a maximum velocity of 30 ft./sec. the maximum kinetic energy is about 2,800 ft./lb./ft.^{2}. This value is appreciably less than the values deduced in Section 3.3 for the energy required to rupture bottom plating. This discrepancy would not matter much if the maximum kinetic energy was a fairly constant proportion of the total available energy. Assuming a given maximum kinetic energy would then be tantamount to assuming a constant total available energy. This is not so, however, using any of the suggested total available energies namely $E_\tau E_v$ and E_h. For conventional high explosive attack the maximum kinetic energy is usually about half the total incident shock wave energy. Damage is found to be proportional to the latter energy so that the maximum velocity is a useful damage criterion for conventional weapons. It is doubtful if the same result holds good for atomic weapons.

For References, see end of Chapter.



SHIP DAMAGE RANGES USING
VERTICAL VELOCITY (V_V) CRITERION



SHIP DAMAGE RANGES USING
HORIZONTAL VELOCITY (V_H) CRITERION

3.6 Comparison of the Various Criteria

Curves of R and H against D are given in figures (1) (2) for the following three cases of interest:-

	Case (a)	Case (b)	Case (c)
Weapon Yield (Radio Chemical)	30	30	1500
Ship Draught (ft.)	34.2	20	20
Critical Value of Energy Prior to Cut-off E_τ (ft. lb./ft.^{2})	5.10^4	$\left(\frac{20}{34.2}\right)5.10^4 = (2.92)10^4$	$(2.92)10^4$
Critical Value of E_v (ft./lb./ft.^{2})	11	do	
Critical Maximum Vertical Velocity (ft./sec.)	30	$30\left(\frac{20}{34.2}\right)^{\frac{1}{2}} = 23$	23

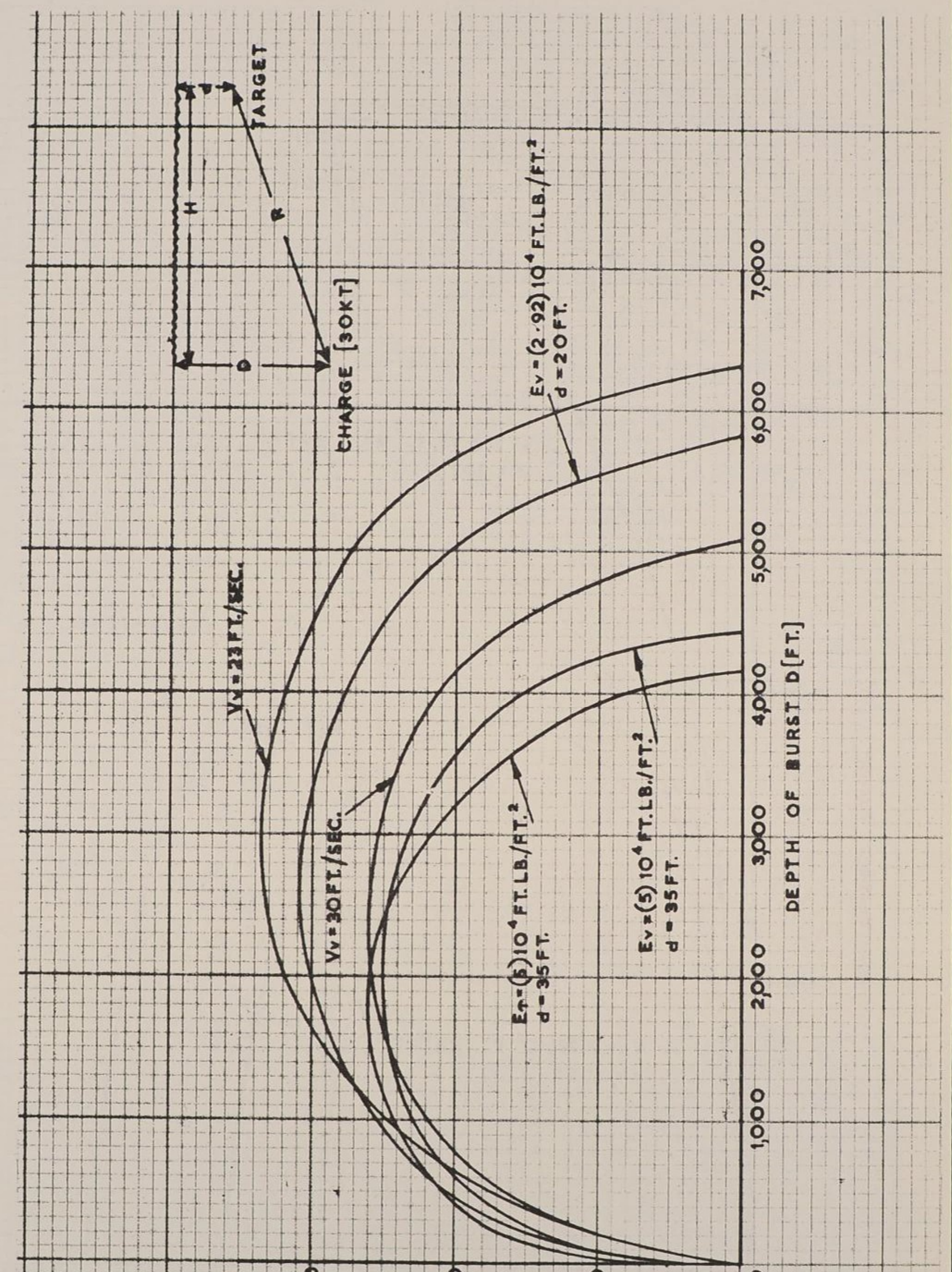
Case (b) was chosen to have E_τ/d and Maximum Kinetic Energy values equal to those for case (a) it being assumed that the mass of the bottom plating varies linearly with the draught.

A noteworthy feature of figures (1) and (2) is that the horizontal ranges given by all the various criteria differ by less than 50% up to the maximum value of horizontal range for 30 K.T. (R.C.V.) and down to a burst depth of 5,000 ft. for 1.5 M.T. (R.C.V.). This is in spite of the very different physical reasoning used for the various criteria and suggests that a mean curve would be quite close to the truth. The curves for the two energy criteria intersect as do the E_τ curve and the V_v curves. Thus no one criterion can be said to give an upper or lower limit to the sinking range.

For the 1.5 megaton charge the values for the sinking range when the charge is directly beneath the ship differ appreciably for the various criteria (the value for $E_v = 2.92.10^4$ ft.lb./ft.^{2}, d = 20 ft. is not plotted, but is D = 39,600 ft.). This is of no practical significance, however, since to detonate a bomb at the maximum depth beneath a ship would be a silly way to attack a ship. There may be some interest in knowing the depth beneath a ship at which it is safe to detonate a bomb of a given size but this will be given by shock and not hull splitting considerations.

The ranges for lethality given by the curve for V_v = 30 ft./sec. (Section 33 figure 1) are probably sufficiently accurate for operational purposes provided that refraction is not important (see Section 3.9).

For References see end of Chapter.



SHIP DAMAGE RANGES:
COMPARISON OF CRITERIA, 30 KT

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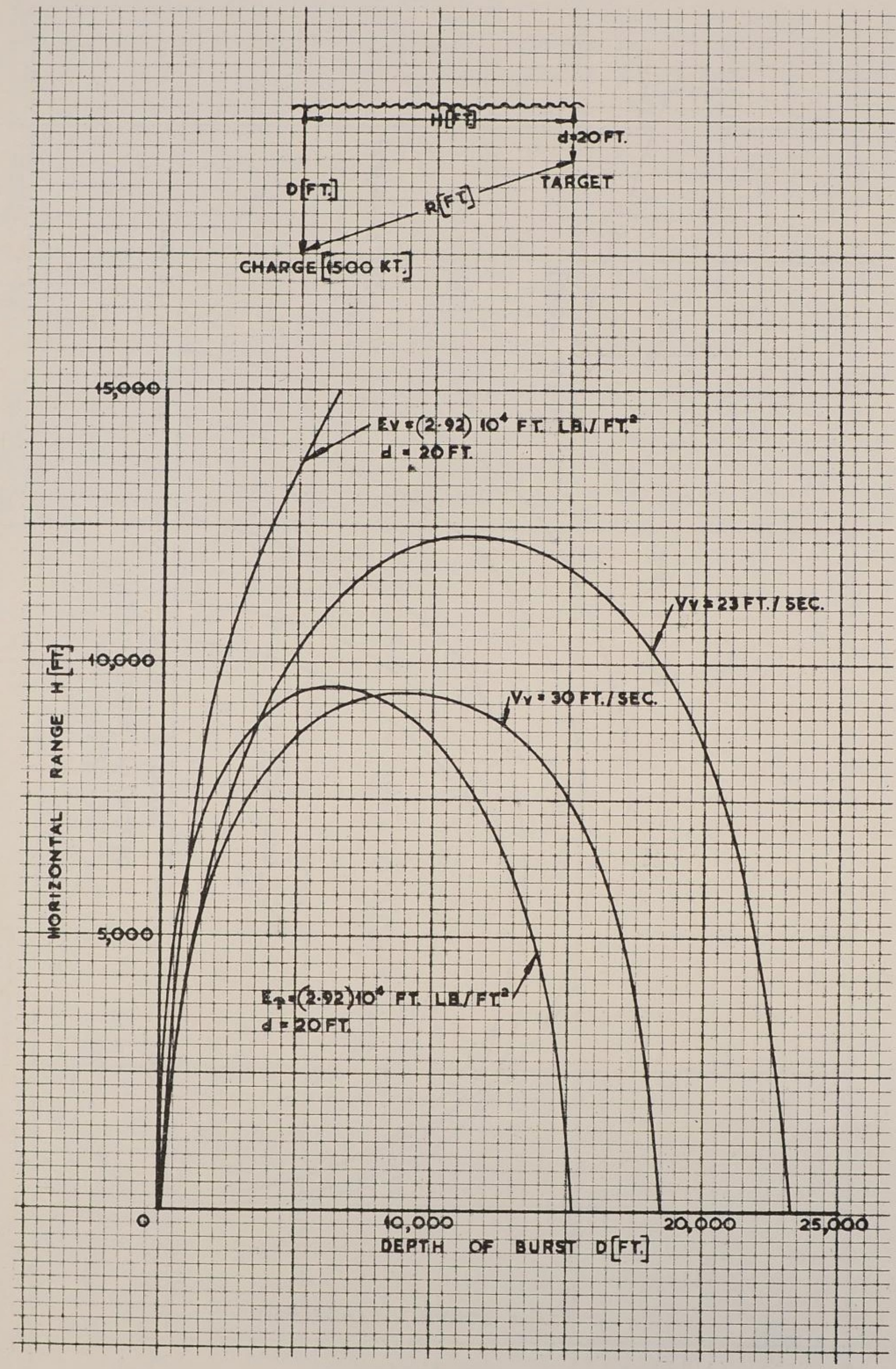

SHIP DAMAGE RANGES:
COMPARISON OF CRITERIA, 1·5 MT

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3.7 Experimental Data

The only full scale data on the effects of atomic weapons on surface ships is that obtained at Bikini Shot BAKER (4) where a 20 K.T. bomb was burst at 90 ft. depth in 180 ft. of water. This data is summarised in Figure (1). The peak underwater shock wave pressure values are not too helpful since the shapes and durations of the pulses are largely unknown. The trial geometry was such that anomalous propagation and bottom reflection were both significant.

Figure (1) shows that every class of ship was sunk within a horizontal distance from the burst of 550 yards. Also no class of ship would have sunk if manned beyond 550 yards. The limiting range for sinking of 550 yards is bracketed most closely for the attack transports and landing craft. The same limiting range for these two widely differing classes of ship give a convincing demonstration that for glancing angle attack the sinking distance is roughly constant for all classes of ship. The same conclusion appears to be valid for serious shock damage.

The lethal radius of submarines submerged to 80 ft. was greater than 900 yards. This is understandable since at this range the peak shock pressure was well in excess of twice the static collapse pressure of the submarines.

A considerable amount of experimental work has been carried out at U.E.R.D. on a 1/35th scale with models of a cargo ship and a cruiser using 106 lb. H.B.X.-1 charges. Little of this work has been reported but some analysed results are given in reference (5). Some of the more important experimental results are given in Table (1) together with values of E_V E_H E_T E_τ V_V and V_H.

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SECTION 3.7 TABLE I (EXPERIMENTAL DATA FROM 1/35th SCALE MODELS)

Geometry (See Figure)		Maximum Bottom Velocity	Permanent Deformations			E_H	E_V	E_T	E_τ	V_v	V_h
R (ft.)	α°	(ft./sec.)	Keel (in.)	Charge Side (in.)	Shadow Side (in.)	(Full Scale) ft.lb./ft.^{2}	(Full Scale) ft.lb./ft.^{2}	(Full Scale) ft.lb./ft.^{2}	(Full Scale) ft.lb./ft.^{2}	(ft./sec.)	(ft./sec.)
45	45	47				$(2.6)10^4$	$(3.74)10^4$	$(6.0)10^4$	$(3.42)10^4$	37	38
30	30	61				$(5.76)10^4$	$(5.51)10^4$	$(13.2)10^4$	$(6.5)10^4$	40	75
50	30	35				$(1.88)10^4$	$(1.94)10^4$	$(4.75)10^4$	$(2.12)10^4$	22	42
68.5	30	25		0.18	0.06	$(0.94)10^4$	$(1.01)10^4$	$(2.52)10^4$	$(1.06)10^4$	16	29
39	15	33				$(2.12)10^4$	$(1.49)10^4$	$(7.75)10^4$	$(2.19)10^4$	15	60
39	30	46		0.7	0.2	$(3.24)10^4$	$(3.22)10^4$	$(7.85)10^4$	$(3.66)10^4$	30	55
20	7.5		0.2	0.2		$(5.41)10^4$	$(3.00)10^4$	$(23.9)10^4$	$(5.45)10^4$	14	130
26	7.5	20				$(3.02)10^4$	$(1.71)10^4$	$(17.3)10^4$	$(3.04)10^4$	11	96

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An interesting feature of the results given in Table (I) is that the measured values of maximum vertical velocity are appreciably higher than the theoretical values. This may seem surprising at first sight since the theoretical values give the vertical particle velocities at a free surface which might be thought to be an upper limit to the vertical velocity. The most plausible explanation is as follows:-

The rigid body response of a submerged circular cylinder, remote from any boundary of the water, to a plane step shock wave travelling at right angles to its axis depends upon its mass. A neutrally buoyant cylinder is accelerated within a few transit times to nearly the undisturbed particle velocity behind the shock front. This case is discussed in Section 4.2. A cylinder of zero mass reaches twice this particle velocity and intermediate densities lead to intermediate rigid body velocities.

The response of the cylinder when only half submerged can be easily deduced by adding the response due to the image charge of negative sign. This addition doubles the vertical velocity and cancels out the horizontal velocity. It is clear therefore that the vertical velocity of a half submerged cylinder is equal to the particle velocity at the free surface for a cylinder which would be neutrally buoyant if fully immersed and twice the value for a cylinder of zero mass. The following simple relation is developed by Bleich and Baron (6).

$$V_v = \frac{4P_m \sin\alpha}{\rho c(1 + \frac{m}{\rho a})} = \frac{2}{(1 + \frac{m}{\rho a})} \text{ (vertical particle velocity at a free surface)} \qquad (10)$$

where m is the mass/unit area of the cylinder
ρ is the density of water
a is the radius of the cylinder

This expression can be written -

$$V_v = \frac{2}{(1 + \frac{W_c}{4\,W_w})} \text{ (vertical particle velocity at a free surface)} \qquad (11)$$

where W_c is the weight of the cylinder/unit length

W_w is the weight of water displaced when half submerged.

Since the vertical velocity should equal the vertical particle velocity when $W_c = 2\,W_w$ it would appear that Bleich and Baron's equation is incorrect and should read -

$$V_v = \frac{2}{(1 + \frac{W_c}{2W_w})} \text{ (vertical particle velocity at a free surface)} \qquad (12)$$

There is apparently an error in their derivation that if corrected would lead to the latter result.

For the more normal case of $W_c = W_w$ the vertical velocity is seen to be 1.33 times the vertical particle velocity at a free surface.

The few values of Charge Side Permament Set given in Table (I) can be seen to have no correlation with the maximum horizontal velocity V_h or the energy parameters E_H and E_τ. There is a better correlation with the parameter E_V and even better with V_V. This suggests that the side deformation is governed mainly by the energy absorbed by the bottom. This is feasible since the cargo ship model had a strong double bottom and rather weak sides. The deformation of the sides was accompanied by and may have been largely the result of vertical displacements of the double bottom.

The trial in which R = 39 ft., $\alpha = 30^\circ$ can probably be regarded as lethal and it is interesting to note that the theoretical vertical velocity of 30 ft./sec. agrees with the value suggested in Section (3.5). Also the value of E_V ($3.22.10^4$) is not greatly different from the value 2.10^4 ft.lb./ft.^{2} suggested in Section (3.3).

For Reference, see end of Chapter.

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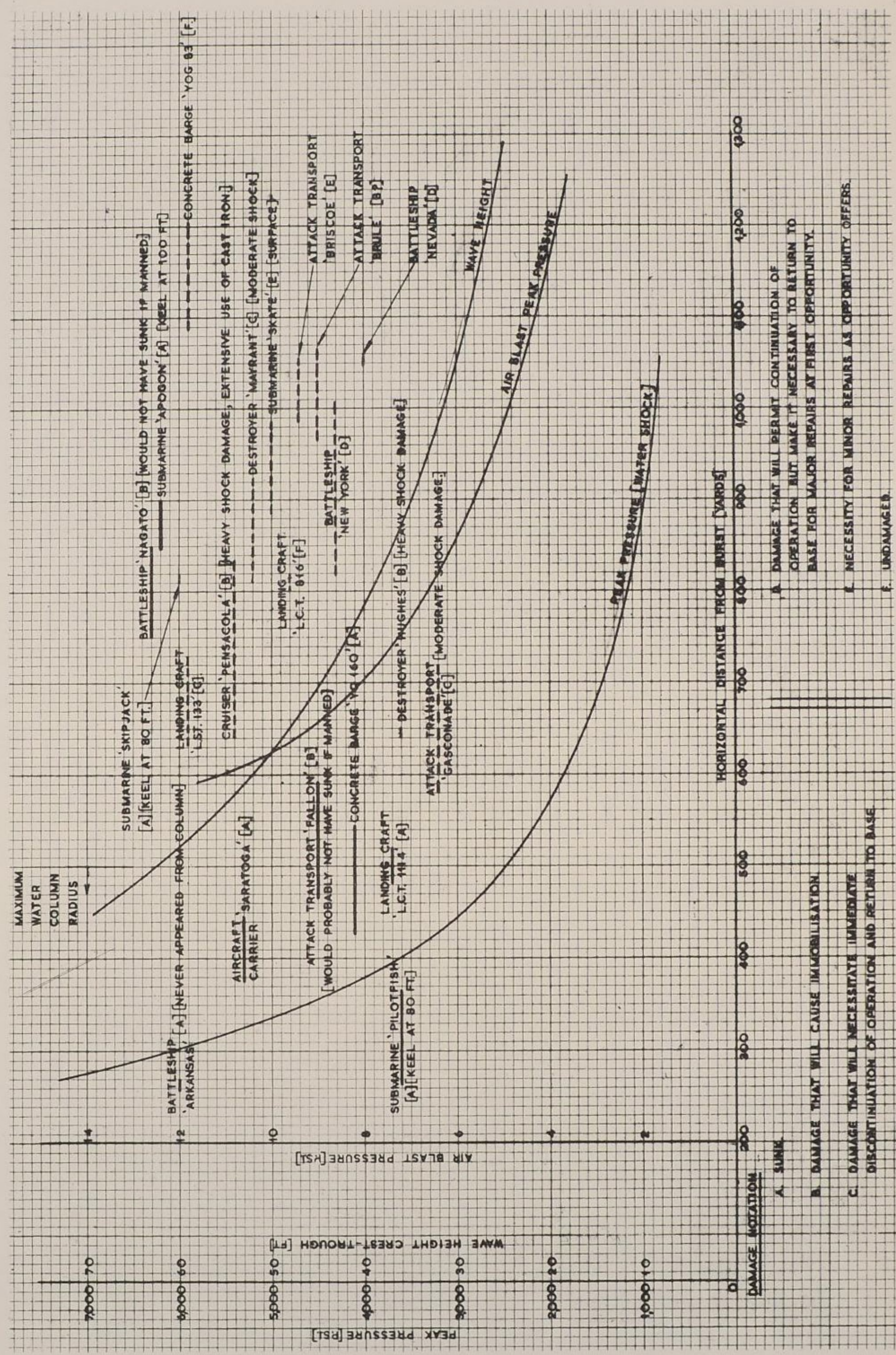


DATA FROM BIKINI

SHOT BAKER

SECRET

3.8 The Effect of Surface Waves on Surface Ships

At the ranges at which the underwater shock wave can do considerable damage the surface waves produced by underwater atomic explosions can be very large. The mechanism of wave formation is discussed in the British "Manual on the Effects of Atomic Weapons" where the following simple formulae are given for wave height etc.

$$\text{Wave height (Crest to Trough) (ft.)} = (4.9)10^4 W^{1/2}/H \qquad (13)$$
$$\text{Wave length (ft.)} = 750\ W^{1/4} \qquad (14)$$
$$\text{Group Velocity (ft./sec.)} = 31 W^{1/8} \qquad (15)$$

where W is the Radio-Chemical Yield expressed in Kilotons of T.N.T. and a bubble equivalent energy of 0.86 W is assumed; H is the horizontal distance from ground zero (ft.). The above wave heights etc. apply when the weapon is exploded near to its venting depth given by

$$V = 240\ W^{1/4}\ \text{(ft.)} \qquad (16)$$

For shallower and greater depths of explosion the wave heights will be somewhat smaller except that for bursts very near the surface slightly larger waves may result.

It is of interest to examine the wave properties at the ranges of interest from the viewpoint of shock wave damage. Assuming that a value of $d/E = 7.10^{-4}$ is lethal for shock wave damage (see Section 3.3), the maximum horizontal range for sinking is given by -

$$H_{max} = 840\ W^{1/3} \quad \text{(assuming a shock wave equivalent weight of } \tfrac{2}{3}\ W) \qquad (17)$$

This maximum horizontal range is obtained for a depth of explosion -

$$D_{max} = 570\ W^{1/3} \qquad (18)$$

At the range H_{max} the maximum wave height H_W is given by $H_W = (58.4)\ W^{1/6}$ (19) if the explosion takes place at a depth V where -

$$D_{max}/V = (2.37)\ W^{1/12} \qquad (20)$$

Numerical examples for several cases of interest are given in Table (I).

Section 3.8 Table (I)

Radio-Chemical Yield	Maximum Wave Height at Shock Wave Sinking Range (Crest to Trough) (ft.)	Wave Length (ft.)	Group Velocity (ft./sec.)	$\left(\frac{D_{max}}{V}\right)$
1 Kiloton	58	750	31	2.37
20 Kilotons	97	1,600	45	3.03
1 Megaton	185	4,200	74	4.22
20 Megatons	300	8,900	109	5.5

Ships are usually designed to have acceptable bending stresses when sitting symmetrically in quasi static equilibrium on a trochoidal wave with

with a wave length and wave height equal to the ship length and 1/20th of the ship's length respectively. The acceptable stress level is usually allowed to increase with the length of the ship and varies from 6 tons/sq.in. for small ships to 10 tons/sq.in. or more for large ships. This variation in acceptable stress allows for the fact that for very long ships say 800 ft. long, waves of 40 ft. high, say, are unlikely to occur and would in any case usually have a wave length greater than the ship length.

These considerations show that the wave heights given in Table (I) may well cause damage by excessive bending of the ship's hull. Detailed calculations of the bending moments are tedious and have not been carried out.

For ships riding on the top of waves, bending actions are likely to predominate. It may happen, however, that a ship plunges into an oncoming wave and in this case serious damage by swamping actions could conceivably occur. To examine this problem theoretically would be difficult, and there is a considerable need for experimental data on this problem.

Some experimental work on the problem of wave damage is in progress at the Naval Construction Research Establishment, but no results are available to date.

For References, see end of Chapter.

3.9 The Effect of Refraction

Using any of the criteria discussed above, the sinking radius increases as $W^{1/3}$ if the charge depth is increased as $W^{1/3}$. If the charge depth is kept constant, the sinking radius varies as $W^{1/4.33}$ using energy prior to cut-off as the criterion, and $W^{1/5.94}$ using a vertical bottom velocity criterion. It is clear therefore that the ranges predicted for megaton weapons are usually in the range 10 - 30,000 feet. In such cases the refraction effects discussed in Section 4.10 can be expected to play a significant part, particularly at the larger ranges. The prediction of pressure histories, and hence of damage to surface ships in heavily refracted regions is not possible at present, but experimental and theoretical work is being carried out in both the U.S.A. and the U.K. This work should eventually make possible the prediction of pressure histories and any of the damage criteria discussed above will be applicable to the pressure pulses obtained.

Ray theory is adequate for assessing the importance of refraction. It is likely that refraction will be of little importance for Kiloton weapons and of far less importance with megaton weapons than is to be expected for submerged submarines, which have far larger damaging ranges.

For References, see end of Chapter.

3.10 Shock Damage to Surface Ships

Damage to machinery etc. by shock is governed mainly by the velocity acquired by the ship's bottom. This velocity can be calculated using figure (1) Section 3.5, bearing in mind that the actual velocity acquired will probably exceed this theoretical value by about 40% (see Section 3.7). The following rough estimates can be made of the effects to be expected at various bottom velocities:

(i) 30 ft./sec. Bottom Velocity

Very severe shock damage leading to immobilisation.

(ii) 20 ft./sec. Bottom Velocity

Severe shock damage to all but the most rugged equipment, possibly leading to immobilisation in warships and almost certainly leading to immobilisation in merchant ships.

(iii) 10 ft./sec. Bottom Velocity

Moderate Shock Damage. Main propulsive machinery probably still operable if designed or suitably protected to withstand shock. A lot of damage to electronic equipment etc.

(iv) 5 ft./sec. Bottom Velocity

Light damage probably confined to electronic equipment lighting fittings etc.

Curves of $H/W^{1/3}$ against $(D-d)/W^{1/3}$ for the above 4 categories of damage are given in figure 1. Comparing these curves with those giving hull splitting ranges shows that severe shock damage will usually occur at ranges greater than those at which hull splitting occurs.

REFERENCES

1. Armament Research Establishment Report 1/48 "The Physical Effects of Atomic Weapons - Part 1 Damage to Ships by Underwater Explosions of Atomic Bombs" by W. G. Penney, January, 1948, (SECRET).

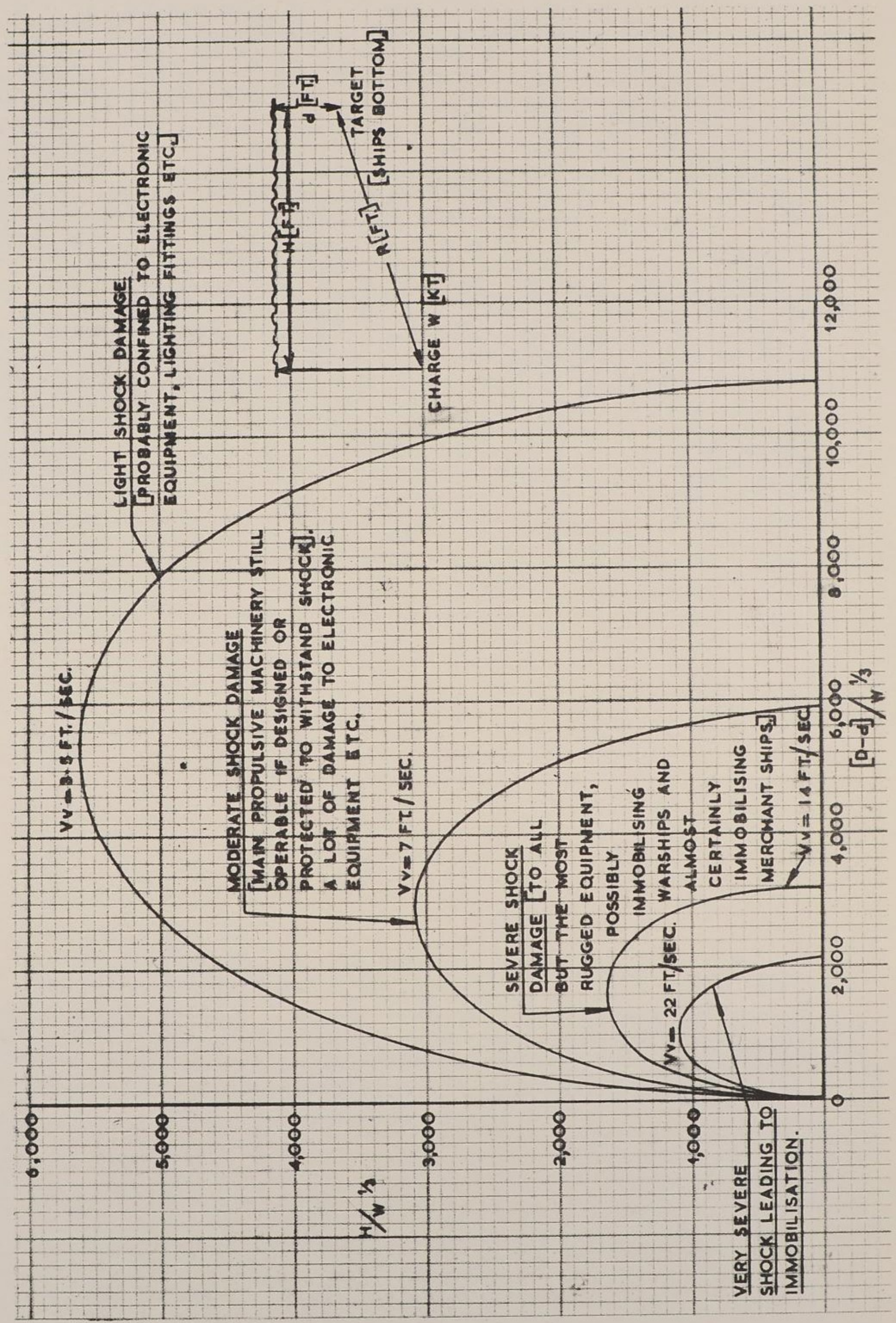
2. U.E.R.D. Report 19-56 "Introduction to Underwater Explosion Research" by A. H. Keil, December, 1956, (CONFIDENTIAL - DISCREET).

3. "Capabilities of Atomic Weapons" T.M.23 - 200 Revised Edition, 1 June, 1955, (CONFIDENTIAL).

4. Atomic Bomb Trials (Operation Crossroads) Report of the British Services Observers at Bikini Atoll, Parts I and II, C.B.004467A and Appendices C.B.004467B, 1946, (SECRET).

5. U.E.R.D. Report 1-57 "Model Studies on Effects of Underwater Atomic Explosions on Ships, Part II - A Selection of Measurements Made in Cargo Ship Model Tests", by W. W. Murray, January, 1957, (CONFIDENTIAL-DISCREET).

6. Baron, M. L. and Bleich, H. H. "Initial Velocity in Shells at a Free Surface due to a Plane Acoustic Shock Wave", Columbia University Department of Civil Engineering and Engineering Mechanics O.N.R. Contract Nonr. - 266 (08), Technical Report No. 19, November, 1956, (UNCLASSIFIED).



SHOCK DAMAGE CURVES
FOR SURFACE SHIPS

CHAPTER 4 - DAMAGE MECHANISMS FOR SUBMERGED SUBMARINES

4.1 The Types of Damage

The damage to submarines caused by underwater explosions from conventional and atomic weapons falls into two fairly distinct types. Firstly the general shaking up of the submarine caused by the shock wave can cause machinery to be displaced or damaged so as to impair the operation of the submarine sufficiently, in severe cases, to cause complete loss. This type of damage is generally referred to as shock damage and can be reduced by the improved design of machinery and mountings. No matter how shock resistant a submarine is made, however, a point is reached as the charge standoff is reduced when hull splitting or gross deformation results which will usually result in the complete loss of the submarine. The standoff at which this occurs, often referred to as the lethal radius, is of particular interest and will be considered first.

The problem is one of considerable difficulty and several lethality criteria based on entirely different collapse mechanisms have been suggested and are more or less tenable. As all of the criteria are based on highly simplified mathematical models, their validity depends upon their agreement with experimental results. Unfortunately insufficient experimental results are available at present to enable any of the criteria to be rejected. These criteria will be described briefly with a discussion of their shortcomings.

4.2 The Mechanism of Hull Splitting

For a deep burst against a deep submarine, when surface cutoff can be neglected, the shock wave from an atomic explosion is quite long compared to the diametral or compartment length of a submarine. This is illustrated in figure (1), where the pressure distance relationship for the shock wave from an explosion of 1.5 K.T., 30 K.T. and 1.5 M.T. Radio-chemical Yield is given for the ranges corresponding to a peak pressure of 1,000 p.s.i. The pressure decays rather little over a range equal to a diameter or compartment length, so the submarine is soon bathed in an almost uniformly high pressure which decays exponentially with time. Since the time constant of the decay is several times greater than the natural period for hull radial vibrations, this may suggest at first sight that when cutoff is not important, the loading may be considered as effectively static. Thus it may be expected that collapse will occur when

$$P_m + P_o = P_c$$

where

P_m is the peak shock wave overpressure
P_o is the hydrostatic pressure at the depth of the submarine
P_c is the static collapse pressure of the submarine.

The problem is not so simple however for the following reasons;

(a) The question of a dynamic factor has to be considered since the loading is suddenly applied. If, as for linear springs under suddenly applied constant loading, the dynamic factor is 2 then yielding and possibly collapse could occur when

$$2\,P_m + P_o = P_c$$

/(b)

(b) Rupture of the hull will only occur if sufficient damage is inflicted by the shock wave loading either to cause hull splitting directly or to reduce the submarine strength below that necessary for withstanding the hydrostatic pressure. To cause this amount of damage will normally take several milliseconds, so just to reach yielding instantaneously in the structure is unlikely to be a sufficient criterion for collapse;

(c) The loading is sufficiently rapid for a dynamic enhancement of the yield stress to take place in most materials.

The question raised in (a) above can only be resolved by studying in detail the response of a cylindrical pressure hull to a slowly decaying shock wave. This problem has been studied by several authors, (References 1, 2, 3, 4, 5) and particular attention has been paid to the case of side-on attack for which several phases occur. The shock wave first hits one side of the section and a reflected wave is generated as the wave front traverses the cylinder. The incident plus reflected pressures cause motions of the hull which in turn induce a relief pressure to be formed at the pressure hull surface and radiated into the surrounding water. The response is rather complex but can be calculated by solving the wave equation in cylindrical co-ordinates with appropriate boundary conditions on the cylinder. The problem is far more difficult than that of a plane wave hitting a plane air backed plate as discussed in Chapter 2, since the relief pressure depends upon the whole time history of the hull motion and not on the instantaneous velocity. For this reason only brief results of some calculations carried out on this problem are presented below.

The radial displacement of the pressure hull for side-on attack can be expressed as the sum of a cosine series:-

$$w(\theta,t) = w_0(t) + w_1(t)\cos\theta + w_2(t)\cos 2\theta$$

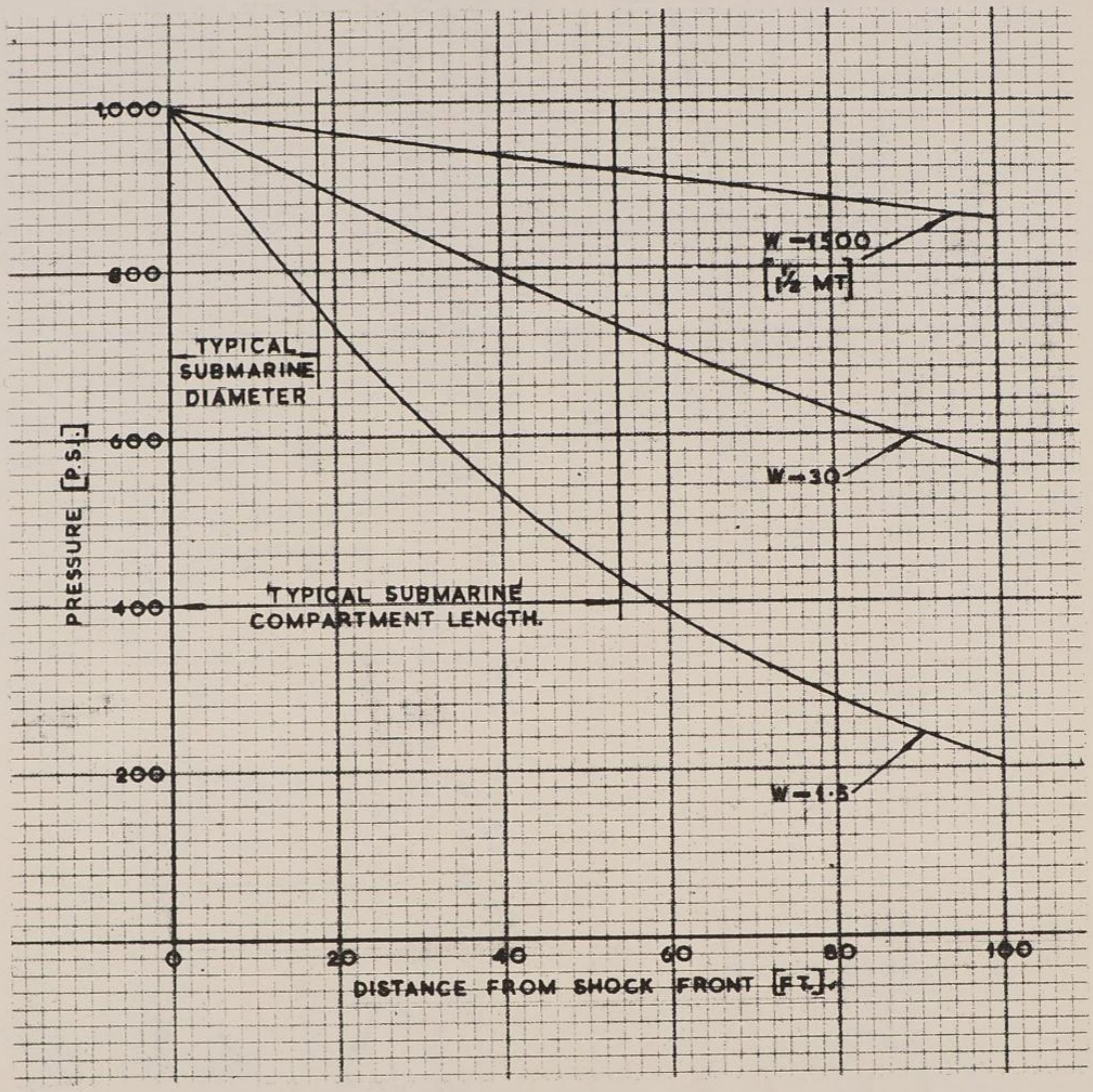
The uniform radial displacement mode $w_0(t)$ is of considerable interest since it is the mode of static deformation and the static collapse pressure is associated with an easily calculated value of this mode. The calculated time history of the uniform radial displacement for a shock wave of time constant 23.8 milliseconds (4,100 ft. from a 10 K.T. burst) impinging side-on to an elastic steel cylinder of radius 100 inches and thickness 1 inch is given in figure (2a). Also given in figure(2a), for comparison, is the static deflection corresponding to the value of the incident pressure at the diametral points A and B. It can be seen that the maximum of the dynamic deformation curve is only 87% of the quasi-static curve maximum. The reason for this lack of overshoot for the case considered is that the relief pressure acts as a damping force of a magnitude that for this mode is nearly critical. A small overshoot of about 5% can occur for more slowly decaying pulses such as are obtained from megaton weapons.

The $w_1(t)\cos\theta$ component of the dynamic displacement fixes the rigid body motion, and is of considerable importance for shock damage studies. The calculated time history of the rigid body mode velocity for a neutrally buoyant cylinder of radius 100 in. attacked side-on by a shock wave of time constant 23.8 milliseconds (4,100 ft. from a 10 K.T. burst) is given in figure (2b). Also shown in figure (2b) for comparison is the particle velocity in the undisturbed shock wave at the diametral points A and B. As might be expected the cylinder velocity never exceeds the particle velocity in the shock wave but acquires very nearly this particle velocity in about 3 transit times (one transit time is the time required by the shock wave to travel over a distance equal to one submarine diameter.).

/The

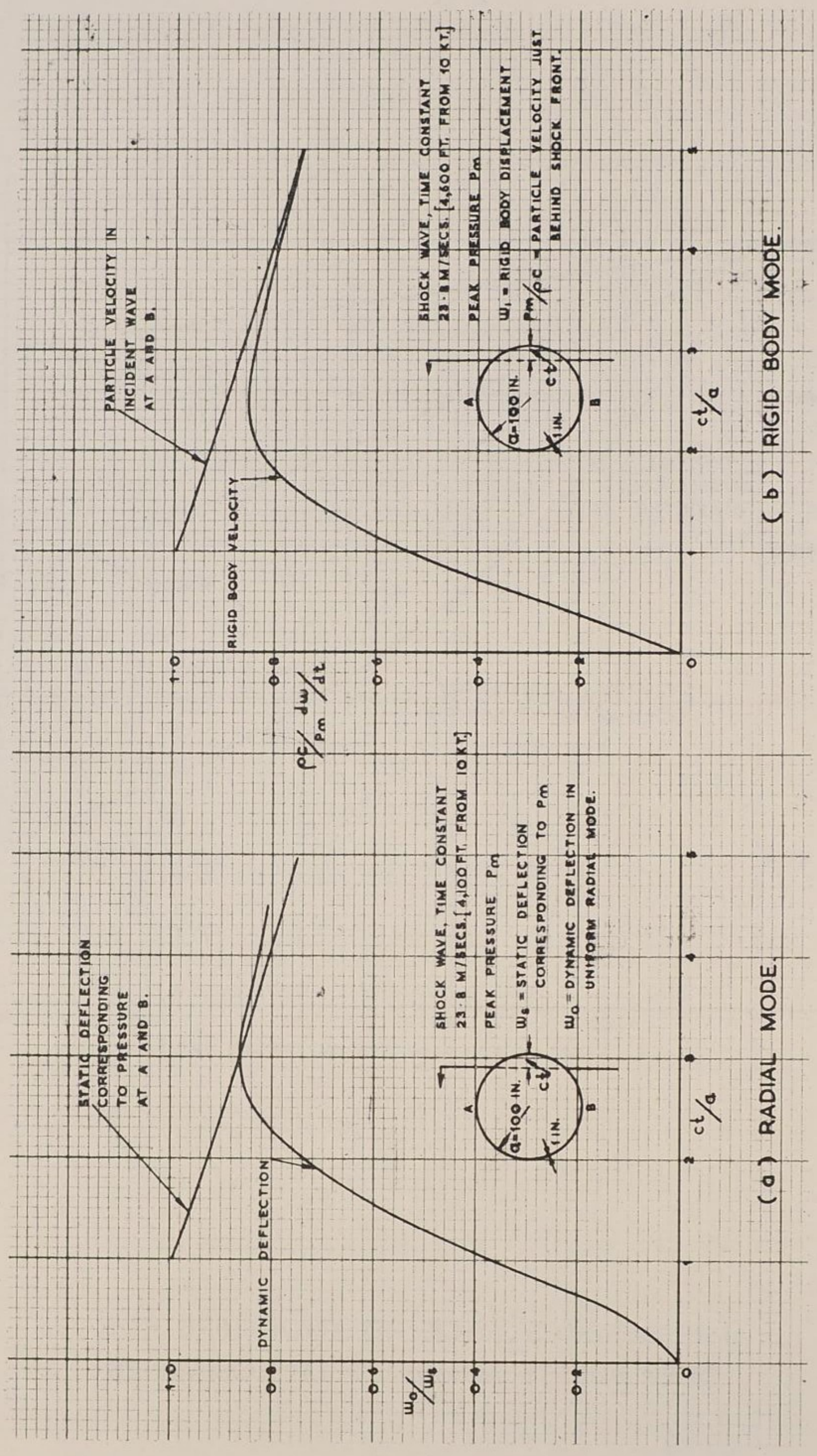
The deformation modes associated with circumferential bending of the hull, $W_2(t)\cos 2\theta$, $w_3(t)\cos 3\theta$ etc. can also be evaulated and several cases of interest have been evaulated in reference (5).

The elastic analysis although complicated can be carried out to any desired accuracy, and has a direct bearing on the problem of shock damage to equipment. The relevance of elastic analysis to the question of plastic collapse is not so clear, except for the understanding which the results give of the degree of hydrodynamic damping to be expected. It is interesting, however, that a lethality criterion has been proposed (6) which uses only elastic analysis and which gives results agreeing quite well with results obtained from an extensive series of small scale experiments. This criterion is described in the next section.



PRESSURE-DISTANCE RELATIONSHIPS FOR DEEP BURSTS AGAINST DEEP SUBMARINES

CONFIDENTIAL



THE RESPONSE OF AN ELASTIC CYLINDER TO AN EXPONENTIALLY DECAYING PLANE SHOCK WAVE

CONFIDENTIAL

4.3 The delayed Yield Criterion

Gooding and Sette (6) have proposed that the collapse of pressure hulls under dynamic loading may be governed by the delayed yield phenomenon which is observed in steel. It is found that when a steel specimen is loaded very rapidly, elastic stresses greater than the static yield stress can be maintained for very short times; the higher the applied stress the shorter the time. A typical delayed yield curve for the submarine steel HTS is shown in figure (1).

An elastic response analysis is carried out for the uniform radial displacement mode allowing for the presence of the ring stiffeners by an increased plating thickness. The circumferential stress is plotted against time as shown in figure (2) and the time at which the dynamic plus the static stress is equal to the static yield stress determined. For subsequent times the average stress is evaluated as a function of T (see figure 2) and plotted on the same co-ordinates as the delayed yield stress curve. Typical curves for two values of P_m are shown in figure (1).

Gooding and Sette have postulated that collapse will occur only if the curve of average stress against T lies above the delayed yield curve at some point. The lethal standoffs deduced from this hypothesis were shown to agree quite well with experimental results obtained in a series of small scale trials (6) (7).

These model tests were carried out over a wide variation in depth and for a wide variety of materials - mild steel, Carbon-Molybdenum steel, high tensile steel, special treatment steel and Aluminium alloy. For each material and over a wide depth range it was found that lethality was associated with a constant value of the ratio

$$P_r = (P_o + P_m)/P_c$$

The experimental data is summarised in figure (3) where values of static collapse pressure P_c and lethal values of $P_m + P_o$ are plotted against yield stress. It is very noticeable that for the steel models, the ratio of dynamic collapse pressure to static collapse pressure decreases from 2.3 to unity as the yield stress increases from 25,000 p.s.i. to 100,000 p.s.i. Gooding and Sette attribute this to the progressively reduced dynamic enhancement of the yield stress as the static yield stress increases. Other explanations are possible (see below). The reduction in dynamic compared to static collapse pressure in the case of the Aluminium alloy models is explained by the very small dynamic enhancement for this material and elastic overshoot due to subcritical damping.

If the delayed yield criterion is generally valid it is clear that model experiments can give results directly applicable to full scale only if the dynamic enhancement of stress plays a small part on model scale. This is because the rapidity of loading is greater on the model than on the full scale so that a greater dynamic enhancement of yield is obtained on the model scale. Another conclusion would be that increases in the static collapse depth of submarines obtained by using steel of increased static yield stress would not lead to a proportional increase in lethal radius. This is because in general the higher the yield stress of a steel the smaller is the dynamic enhancement for a given rate of loading.

Although the delayed-yield criterion explains adequately the experimental results of Gooding and Sette, the following objections can be raised

(1) The method is very sensitive to the delayed yield curve. This curve is not too well defined and data from different investigators deviate considerably.

(2) The decreasing value of P_r for increasing yield stress can be at least partly explained by the fact that keeping the dimensions constant and increasing the yield stress leads to models of unbalanced design with relatively weak frames. This could be expected to lead to poor dynamic performance.

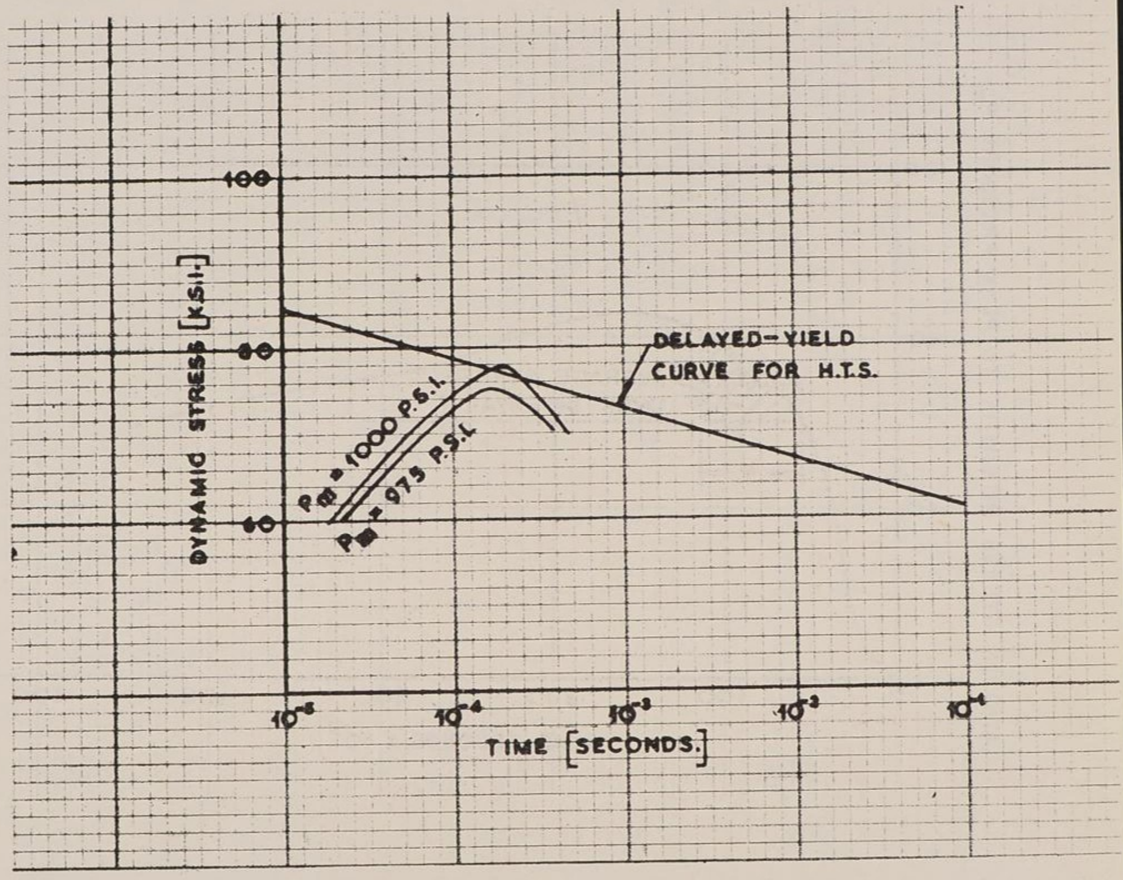
(3) Strain hardening and strain rate effects can be expected to play a part but these are neglected.

(4) Delayed yield may well not occur at all in full scale welded structures.

(5) The mean deflection at the instant when the mean stress versus T curve touches the delayed-yield curve is much less than one plating thickness whereas deformations of several plating thicknesses are necessary for rupture.

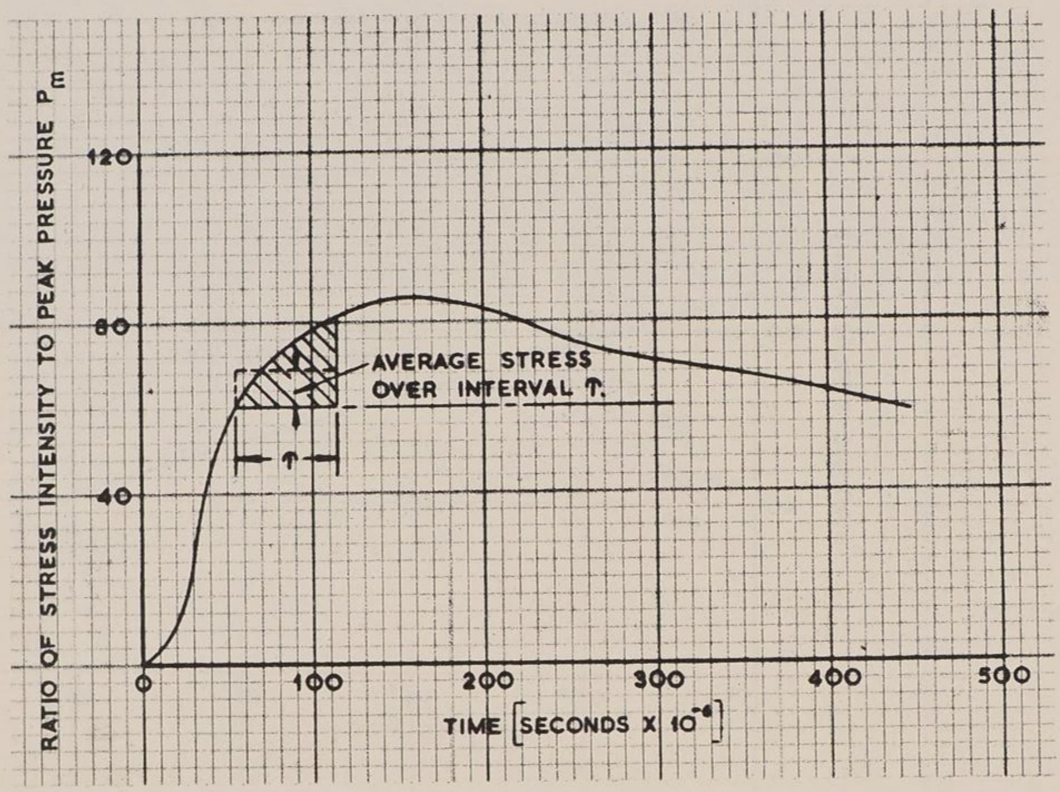
(6) The bending stiffness of the frames is known to play a significant part in explosion resistance but is not allowed for in the criterion.

For References see end of Chapter.

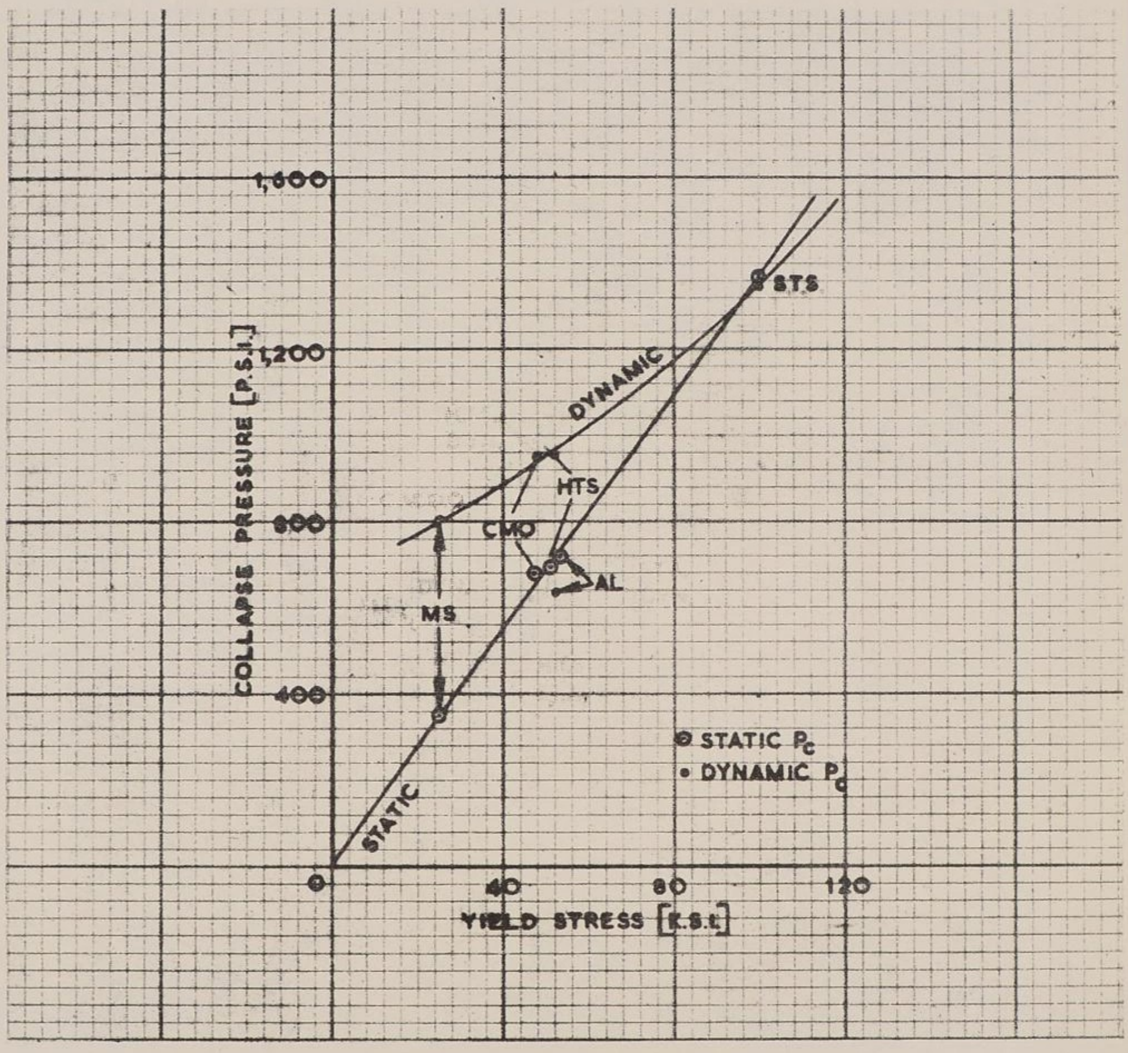


DELAYED YIELD CURVE FOR
SUBMARINE STEEL

PART V
CHAPTER 4
SECTION 4.3
FIGURE 2



CIRCUMFERENTIAL STRESS OF SUBMARINE
STEEL AS A FUNCTION OF TIME



STATIC AND DYNAMIC COLLAPSE PRESSURES
AS FUNCTIONS OF YIELD STRESS

4.4 Elastic-Plastic Response of Cylindrical Shells to Shock Waves

From the mathematical viewpoint it is not necessary to confine response calculations to the purely elastic phase. Provided that the relation between stress, strain and strain rate are known beyond the elastic limit the calculations can be carried into the plastic region. Using the full hydrodynamic equations this would be difficult, but Haywood (5) has developed a simple method of solution which gives accurate answers. Considering only the uniform radial displacement mode the governing differential equations for the motion of the cylinder can be written

$$m\ddot{w} + \sigma h/a = P_o + P_i - P_r \qquad (1)$$

$$\dot{w} = P_r/\rho c + \left(\frac{0.363}{\rho a}\right)\int_0^t P_r dt \qquad (2)$$

where m is the mass/unit area of the shell plating

- h is the shell plating thickness (in.)
- a is the mean shell radius
- ρ is the density of water
- c is the velocity of sound in water
- w is the displacement radially inwards
- P_i is the incident shock wave overpressure
- P_o is the static pressure
- P_r is the relief pressure
- σ is the stress in the shell plating (a function of w and possible $\dot{w}$)

Neglect of the inertia terms $m\ddot{w}$ leads to errors only at very small times.

The equations can be solved numerically in any particular case and the evaluation of a large number of cases taking different stress-strain/strain-rate relationships would give a much better understanding of the response mechanism. Unfortunately this would be very time consuming without electronic computing and has not been attempted. Another snag is that little is known about the relation between stress-strain and strain-rate for steel.

Since a purely theoretical solution to the problem of submarine lethality is not at present possible, it is necessary to resort to semi-empirical rules based on highly simplified mathematical models. The justification for the use of these rules lies almost entirely in their agreement with experimental results.

4.5 The Excess Energy Criterion

It is obviously worth considering whether the lethal severity formulae for conventional weapons still hold for atomic weapons. A very well known equation for conventional charges against shallow submarines with a yield stress of about 18 tons/sq.in. is the Hogg formala.

$$w = (0.75)hR\sqrt{R^2 + 110} \simeq (0.75)hR^2 \text{ for large charge weights} \qquad (3)$$

where h is the shell plating thickness (in.)

w is(the charge weight expressed in lb. T.N.T.
R is the lethal standoff (ft.)

When modified to allow for depth of submergence and yield point variation the Hogg formula for large charges becomes

$$w = (0.75)h(\sigma_y/18)R^2[1 - (P_o/P_c)^{3/2}] \qquad (4)$$

where σ_y is the yield stress (tons/sq.in.)

P_o is the static pressure
P_c is the static collapse pressure

For a given submarine at a given depth the lethal radius given by (4) varies as $W^{\frac{1}{2}}$. Thus, since the peak shock wave pressure is proportional to $(W^{1/3}/R)^{1.13}$, the peak pressure at lethality is proportional to $W^{-1/4.3}$ and eventually for large charge weights drops to values less than the collapse pressure margin $P_c - P_o$. This shows that equation (4) cannot be true for very large charge weights. The physical explanation is that equation (4) is based on the assumption that a constant value of the energy flux

$$E = \int_0^\infty (P_i^2/\rho c)dt \qquad (5)$$

is required for lethality. For the long duration shock waves obtained from atomic explosions the required value of energy flux can be obtained with relatively low peak pressures.

This difficulty can be overcome by considering only the energy flux up to the instant when the shock wave equals the collapse pressure margin $P_c - P_o$. The equation then becomes

$$w\left\{1 - \left(\frac{P_c - P_o}{P_m}\right)^2\right\} = (0.75)h(\sigma_y/18)R^2[1 - (P_o/P_c)^{3/2}] \qquad (6)$$

and it can be seen that the following limiting values hold

$P_m = P_c - P_o$ as $W \to \infty$

$R \to \infty$ as $P_o \to P_c$

The first limiting value is probably very nearly correct since very little dynamic overshoot may be expected. The second limiting value is obviously correct. Unfortunately another objection exists against both equations (4) and (6) which can best be discussed by means of a numerical example as follows.

For a submarine with a collapse pressure of 500 p.s.i. at a depth of 500 feet with a pressure hull thickness of 1 inch and a yield stress of 27 tons/sq. in. equation (4) gives

/R =

$R = (1.13)w^{\frac{1}{2}}$

For $W = 30$ kilotons, $w = 4.10^7$ lb., $R = 7{,}100$ ft., $P_m = 700$ p.s.i.
$P_r = (P_m + P_o)/P_c = 1.84$

Experimental evidence suggests that this value of P_r is likely to be too high for normally framed submarines of reasonably high yield stress. A value of $P_r = 1.4$ is more likely for a 20 kiloton weapon. Thus we have the surprising result that for a 30 K.T. weapon the Hogg formula gives a value for the lethal radius which is too small. Since the variation of lethal radius with charge weight is likely to change from a square root to a cube root law as the charge weight increases, the lethal radius value for 30 K.T. obtained by keeping to the square root law would be expected to be too large and not too small. The difficulty is illustrated in figure (1) where the relation $R = 1.13\ w^{\frac{1}{2}}$ is plotted on a log scale. The point obtained from the condition $P_r = 1.4$ for $w = 4.10^7$ is also plotted and it is clear that any curve passing through this point and tangenial to the Hogg formula curve for $w < 10^3$ needs to have a slope greater than $w^{\frac{1}{2}}$ in at least part of the intermediate region. Such a slop is unlikely to be correct and the inference is that the Hogg formula is in error. The modification leading to equation (6) makes things worse since it leads to smaller values of lethal radius.

An alternative and more recent lethal radius formula for conventional charges based on energy flux considerations is that due to Schauer (8). The original equation is expressed in terms of the American explosive HBX but it can be modified for T.N.T. into the following form

$$w^{1.0} = (21.2)R^{2.02}\ h\ \left(\frac{h^3}{d^2}\right)^{1/4} \sigma_y S \left[1 - \frac{P_o}{P_c}\right] \qquad (7)$$

where w, h, P_o, P_c are defined above

σ_y is the yield stress (10^3 p.s.i.)
d is the pressure hull diameter (ft.)
S is a frame strength parameter defined in figure (2).

The use of the Schauer formula for atomic weapons suffers from the objections discussed above. This is **illustrated** by the full line curve of figure (3) where the Schauer formula for the explosive HBX is plotted with $P_m/(P_c - P_o)$ as the ordinate and $F/(P_c - P_o)\theta^{5/4}$ as the abscissa, where

F is a factor depending on the detail design of the pressure hull
θ is the shock wave decay constant

The experimental results shown plotted are for charge weights much less than 1 K.T. full scale and the agreement with the Schauer formula is seen to be good. For the reasons discussed above the Schauer curve gives values for $P_m/(P_c - P_o)$ which are less than unity for large atomic weapons. For this reason the Schauer formula, and indeed the whole energy flux concept for predicting lethal radii, is rejected in reference (9). However, the simple remedy of considering only the energy flux up to the instant when the shock wave pressure equals the collapse pressure $P_c - P_o$ overcomes this difficulty. The modified equation is

$$w^{1.09} \left\{1 - \left(\frac{P_c - P_o}{P_m}\right)^2\right\} = (21.2)R^{2.02}\ h \left(\frac{h^3}{d^2}\right)^{1/4} \sigma_y\ S \left(1 - \frac{P_o}{P_c}\right) \qquad (8)$$

/and

and this equation gives the dotted curve of figure (3). The experimental results agree as well with the dotted curve as with the full curve and the dotted curve asymptotes to the desired value $P_m/(P_c - P_o) = 1$ as $\theta \to \infty$.

For the numerical example of figure (4), the lethal radius for a 30 K.T. (Radio Chemical Yield) explosion ($w = 4.10^7$) given by equation (8) is 8400 ft. giving a value for $P_r = (P_m + P_o)/P_c = 1.61$. This value for P_r is still somewhat higher than might be expected (see above) and for other submarine designs, the values of P_r for a 30 K.T. charge against the submarine at 500 ft. submergence can rise as high as 2. This suggests (but by no means proves) the inadequacy of the modified Schauer formula.

To overcome this difficulty about the value of P_r obtained for 30 K.T. charges it is possible to use the following more general lethal radius equation based on energy flux ideas.

$$w\left\{1 - \left(\frac{P_c - P_o}{P_m}\right)^2\right\} = AR^2\left\{1 - \left(\frac{P_o}{P_c}\right)^{\gamma}\right\} \tag{9}$$

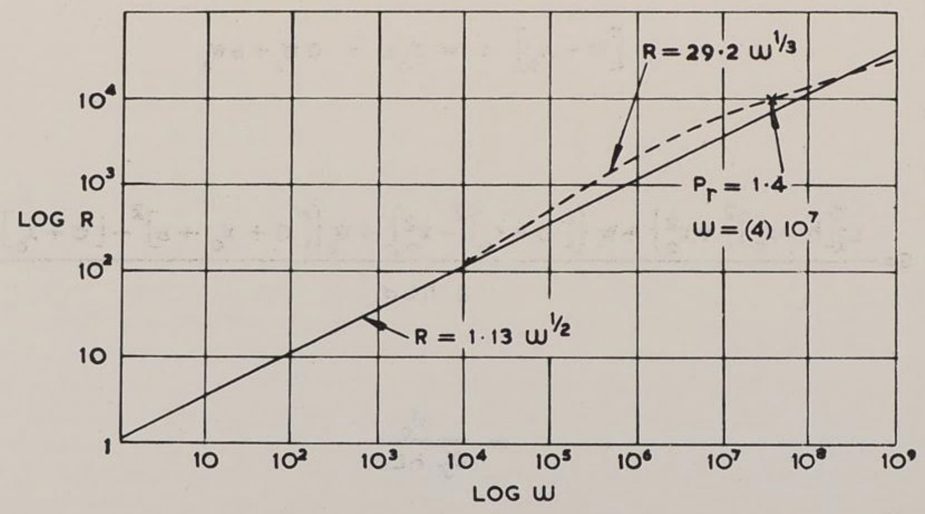
where A is a constant to be determined. If it is stipulated that $(P_m + P_o)/P_c = P_r$ when $w = w_1$ and $P_o = \beta P_c$, A becomes

$$A = w_1^{\ 1/3}\left\{1 - \frac{(1-\beta)^2}{(P_r - \beta)^2}\right\}\left\{\frac{P_r - \beta)P_c}{21,600}\right\}^{1.77} / (1 - \beta^{\gamma}) \tag{10}$$

if $P_m = 21,600\ (w^{1/3}/R)^{1.13}$. For the particular case of interest when $w_1 = 4.10^7$,

$$\gamma = 1,\ \beta = 0.5,\ P_r = 1.4$$
$$A = (83.6)10^{-7}\ P_c^{\ 1.77} \tag{11}$$

The constant A of equation (10) can be chosen to give any desired lethal radius for a particular set of values w, P_c, P_o. The value of this is that only one experimental result is required to enable lethal radii predictions for different charge weights and depths of submergence to be carried out. The particular value for A given in equation (11) is based on the experimental evidence available to date, namely, that for a 30 K.T. charge a value $P_r = 1.4$ is about right for a deeply submerged submarine.



RELATIONSHIP BETWEEN LETHAL RADIUS AND CHARGE WEIGHT

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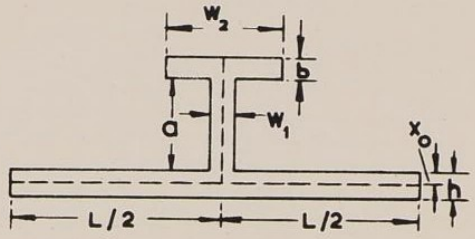


$$\left[h - x_o\right] L = x_o L + a W_1 + b W_2$$

$$S = \frac{L\left\{\left[h - x_o\right]^2 + x_o^2\right\} + W_1\left\{\left[a + x_o\right]^2 - x_o^2\right\} + W_2\left\{\left[a + x_o + b\right]^2 - \left[a + x_o\right]^2\right\}}{2\,hLd}$$

$$= \frac{M_o}{\sigma_y\, hLd}$$

M_o = PLASTIC MOMENT OF STIFFENER AND ONE FRAME SPACING OF HULL PLATING.

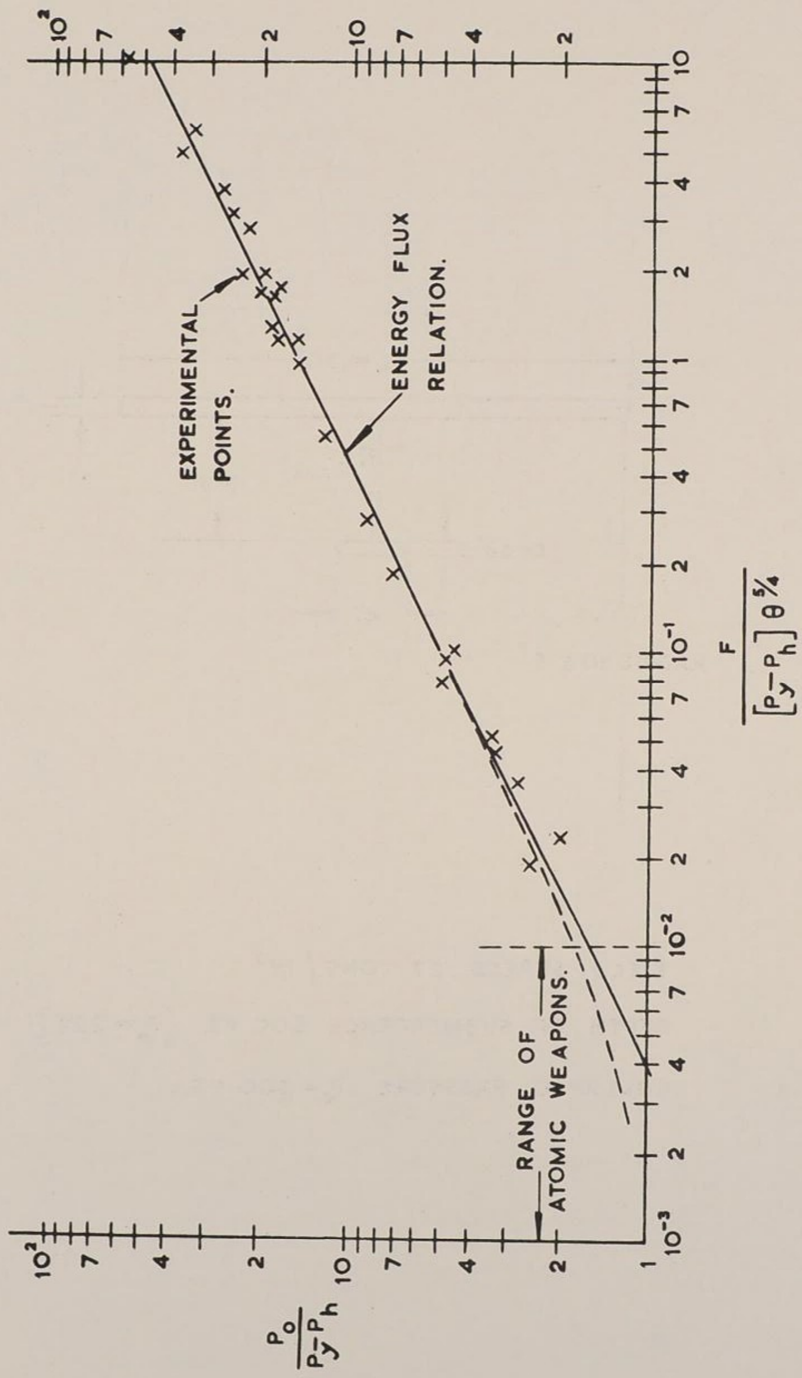
h = HULL THICKNESS. [IN.]

L = FRAME SPACING. [IN.]

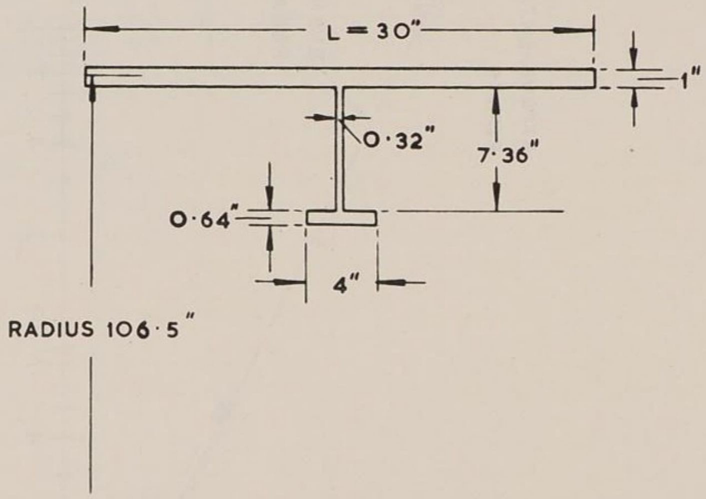
d = HULL DIAMETER. [IN.]

σ_y = YIELD STRESS.

DEFINITION OF FRAME STRENGTH PARAMETER [S]



SCHAUER LETHAL RADIUS
FORMULA FOR HBX



YIELD STRESS 27 TONS / IN²

DEPTH OF SUBMERGENCE 500 FT. $[P_o = 222]$

COLLAPSE PRESSURE $P_c = 500$ P.S.I.

NUMERICAL EXAMPLE OF MODIFIED SCHAUER FORMULA

4.6 The Excess Impulse Criterion

Perhaps the most plausible lethality criterion yet proposed is that based on excess impulse which considers that lethality is associated with a given value of the parameter

$$I_e = \int_0^{t_1} (P_i + P_o - P_c)dt \qquad (12)$$

where P_i is the incident shock wave overpressure
t_1 is the time at which $P_i = P_c - P_o$

When $P_i = P_m e^{-t/\theta}$ the excess impulse neglecting surface cut off becomes

$$I_e = (P_m \theta) - [(P_c - P_o)\theta]\ [1 + \log_e \{P_m/(P_c - P_o)\}] \qquad (13)$$

The critical excess impulse will vary for each class of submarine but Keil (9) suggests that

$$(I_e)_{\text{critical}} = 2.13\ h\ \text{p.s.i. - secs.} \qquad (14)$$

where h is the plating thickness in inches.

It will not be demonstrated that under certain simplifying assumptions the maximum uniform radial displacement of a circular cylinder is proportional to the excess impulse: Under attack of lethal or near lethal severity, the response of a pressure hull becomes inelastic at fairly small times when the mean radial displacement is small compared to the plating thickness. Assuming that, beyond the elastic limit, plane wave damping applies, inertia effects are insignificant and the yield stress is dynamically enhanced so that

$$\sigma = \sigma_y + K\,\dot{w}_o/a \qquad (15)$$

the differential equation of motion may be written

$$\left(\frac{h}{a}\right) [\sigma_y + K\,\dot{w}_o/a] + \rho c \dot{w}_o = P_i + P_o \qquad (16)$$

$$\text{i.e. } \dot{w}_o = (P_i + P_o - P_y)/(\rho c + hK/a^2) \qquad (16)$$

where $P_y = h\sigma_y/a \simeq P_c$. Integrating equation (15) gives

$$w_{op} = \frac{1}{[\rho c + (hK/a^2)]} \int_0^{t_1} (P_i + P_o - P_c)dt \qquad (17)$$

where w_{op} is the maximum plastic deformation

t_1 is the time at which $P_i + P_o = P_c$

$$\text{i.e. } w_{op} = I_E/[\rho c + (hK/a^2)] \qquad (18)$$

Taking the critical value I_e given in equation (14) leads to the following expression for the critical value of w_{op}

$$(w_{op})_{max} = \frac{(0.37)h}{1 + (0.173)hK/a^2} \qquad (19)$$

Thus according to this simplified theory $(w_{op})_{max}$ cannot exceed 37% of the plating thickness if collapse is to be avoided. This critical value for the mean radial displacement may seem surprisingly low but the mean displacement possibly serves as a trigger for bending distortions of the framing which would soon lead to much larger deflections. The assumption of plane wave hydrodynamic damping also reduces the mean deflection value obtained since the afterflow term in the hydrodynamic equation (16) has the effect of reducing the relief pressure.

4.7 The Effect of Surface Cut-Off

The discussion of lethality criteria for submarines has so far been confined to attack geometries such that

either (1) the curve of average stress versus T (see Section 4.3) touches the delayed yield stress curve.
(2) the critical excess energy value is reached
(3) the critical excess impulse value is reached

before the arrival of the surface cut-off which effectively reduces the incident pressure to zero. In very many cases of interest, however, this will not be the case and it is necessary to examine the effect of cut-off on lethal radii.

It is possible to carry out the calculation for the delayed yield criterion, described in Section 4.3, allowing for cut-off by taking the incident pressure as

$$P_i = P_m e^{-t/\theta} \text{ for } t \leqslant \tau$$

$$P_i = 0 \text{ for } t > \tau$$

where τ is the cut-off time. The linearity of the problem makes this simply a matter of adding the solutions obtained to the following problems

Case (a) $P_i = P_m e^{-t/\theta} \quad 0 \leqslant t \leqslant \infty$

Case (b) $P_i = 0$ for $0 \leqslant t \leqslant \tau$ $P_i = P_m e^{-\tau/\theta} e^{-t'/\theta}$ for $t = t' + \tau > \tau$

The solution to case (b) is clearly the same as for case (a) times a factor $-P_m e^{-\tau/\theta}$ and with change of time origin. Using this approach the effect of cut-off on the response shown in figure (2) Section 4.2 has been calculated and is shown in figure (1) for varying values of the cut-off parameter $c\tau/a$. The increase in deflection after cut-off occurs is of particular interest. This increase is very small for cut-offs as late as 1.5 times the transit time $2a/c$ rising to about 20% for small cut-off times. The increase in deflection after cut-off is due to inertia effects and since the inertia of the shell plating is too small to account for an increase of as much as 20%, the effect must be principally due to the effective additional inertia of the water. Put another way, the motion of the cylinder radially inwards involves a radially inwards movement of water. The arrival of the plane wave associated with cut-off can have no direct effect on this radial movement of water which has to be slowed down and stopped by the elastic resistance of the cylinder.

To allow for the effect of cut-off on the excess energy and excess impulse criteria it is necessary to evaluate both the cut-off time

$$\tau = (R/c) \left\{1 + \left(\frac{4dD}{R^2}\right)\right\}^{\frac{1}{2}} - (R/c) \qquad (20)$$

and the time

$$t_1 = (\theta) \log_n \left(\frac{P_m}{P_c - P_o}\right) \qquad (21)$$

where R is the slant radius
d is the depth of submergence of the submarine
D is the charge depth
c is the velocity of sound in water
θ, P_m, P_c and P_o have been defined previously.

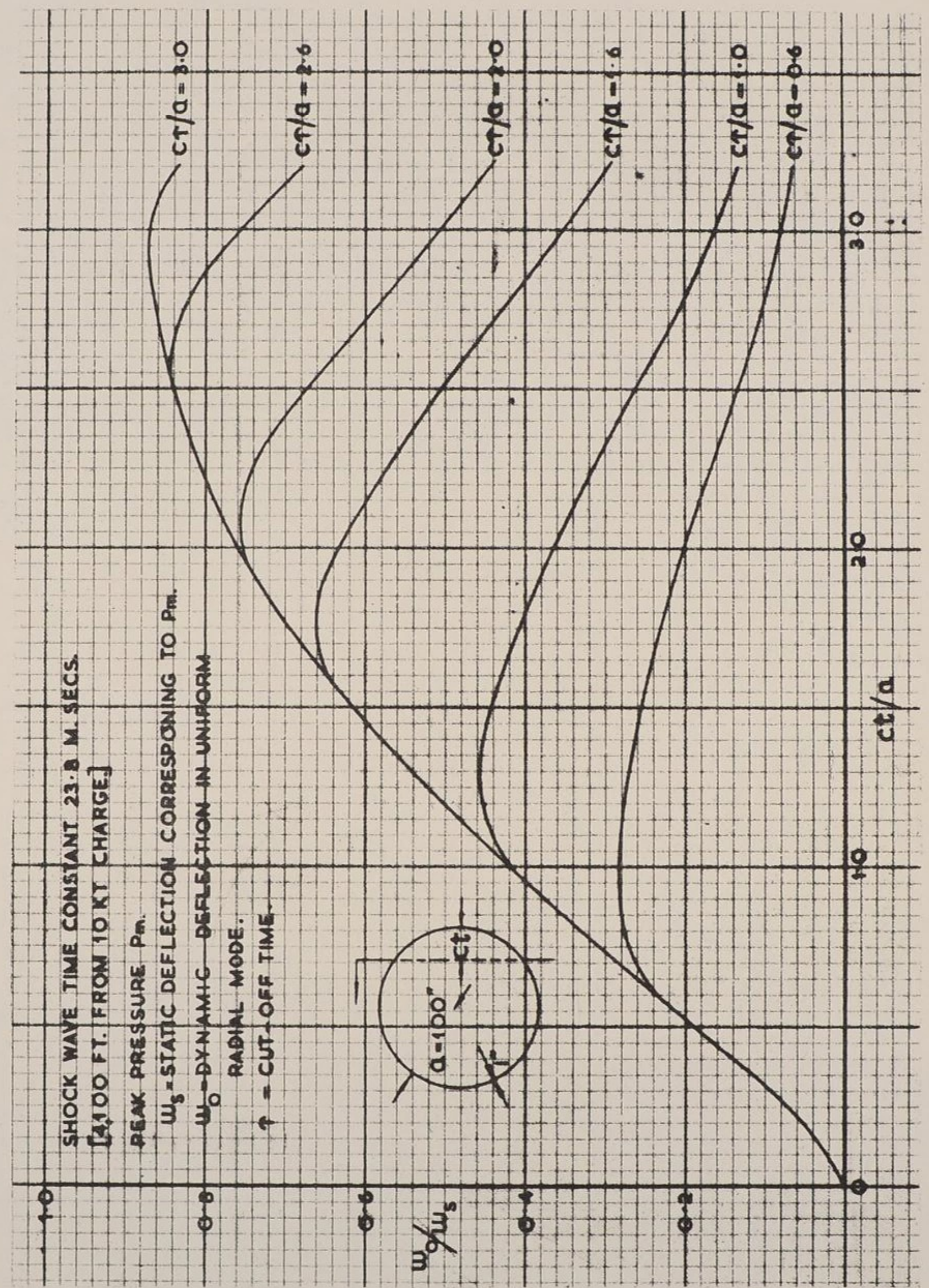
If $\tau > t_1$, cut-off has no effect and equations (9), (13) still hold. If $\tau < t_1$, cut-off has the effect of reducing the lethal radius and the following equations hold.

For excess energy

$$w \left\{ 1 - e^{-2n\tau} \right\} = AR^2 \left\{ 1 - \left(\frac{P_o}{P_c} \right)^{\alpha} \right\} \qquad (22)$$

For excess impulse

$$I_E = P_m \theta \left\{ 1 - e^{-n\tau} \right\} - (P_c - P_o)\tau = (2.13)h \qquad (23)$$



THE EFFECT OF SURFACE CUT - OFF ON ELASTIC RESPONSE
IN THE RADIAL MODE

4.8 Comparison of Excess Impulse and Energy Criteria

It is of interest to see how the lethal radii values obtained using the "Excess Impulse" and the "Excess Energy" criteria compare numerically. For this purpose several examples of interest have been calculated and are shown in the following Table (1).

TABLE I

Lethal Radii in the Absence of Refraction, Cavitation, etc.

Weapon Yield W	Collapse Pressure (p.s.i.)	Excess Impulse (p.s.i. sec.)	Charge Depth (feet)	Submarine Depth (feet)	Lethal Radii (ft.)	
					Excess Impulse	Excess Energy
1.5	500	2.13	500	50	1810	1525
"	"	"	"	500	2670	2480
"	"	"	2000	50	1920	1820
"	"	"	"	500	2670	2480
30	"	"	500	50	3900	3610
"	"	"	"	500	8970	8220
"	"	"	2000	50	4900	5390
"	"	"	"	500	9740	9840
3000	"	"	500	50	15800	17900
"	"	"	"	500	43700	44500
"	"	"	2000	50	25800	27700
"	"	"	"	500	73500	67700
30	670	3.1	500	50	3190	3050
"	"	"	"	500	6330	6420
"	"	"	2000	50	4610	4500
"	"	"	"	500	6410	6740

The agreement between the lethal radii obtained from the two criteria is seen to be good (within 7% on average) in fact so good that experimental work could not be expected to provide a valid choice between the two criteria. The "Excess Energy" criterion is slightly the easier to compute and should give reasonably correct answers for lethal radius for most cases of interst apart from those in which refraction plays a large Part. (See Section 4.10).

4.9 The Effect of Cavitation

The lethal radii values given in Table (1) Section (4.8) show marked reductions for shallow submergence of submarine and bomb. These reductions are due to the effect of surface cut-off which reduces the shock wave pressure to near zero whilst increasing the vertical particle velocity and decreasing the horizontal particle velocity. The possible damaging power of the increase in vertically directed kinetic energy has been neglected, perhaps unjustifiably.

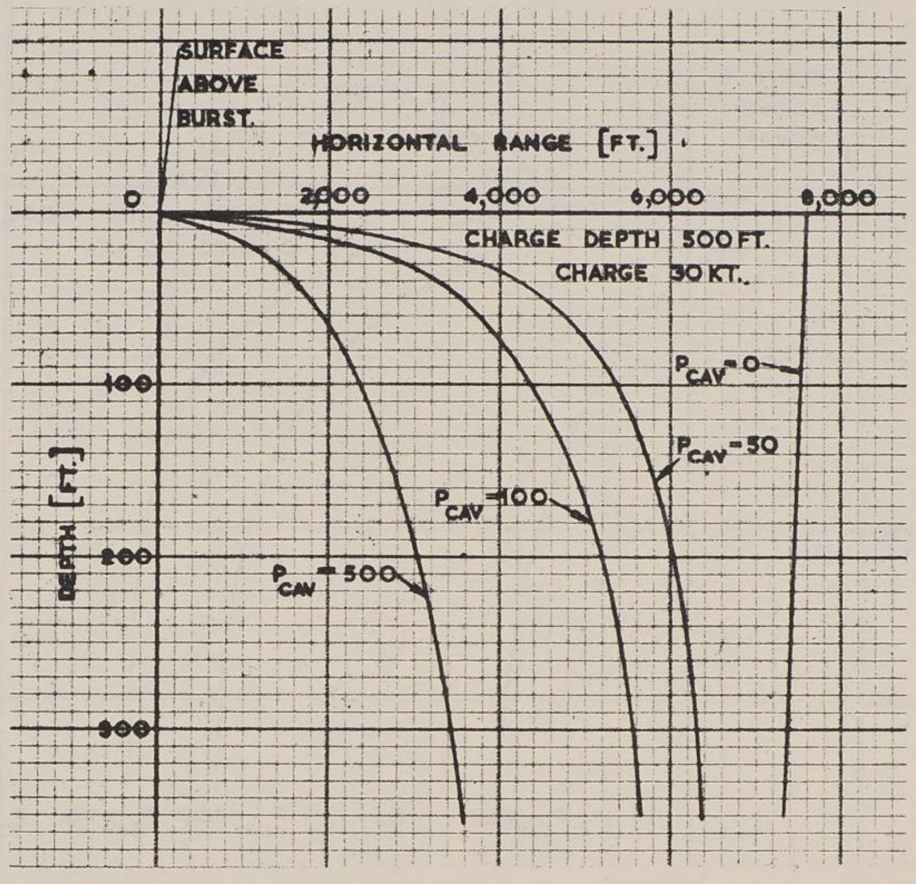
If sea water could withstand tension, the sea surface would reflect all the shock wave energy as a tension wave. However due to the finite and probably very small tensile strength of sea water cavitation will usually occur and considerably modify this process. Curves showing the positions at which tensions of various magnitudes are first reached (cavitation inception surfaces) are shown in figures (1) - (4) for several cases of interest. The actual cavitation tension of sea water is probably less than 50 p.s.i. for shock waves from atomic explosions. The water above a cavitation inception surface can be expected to separate from the sea beneath. This water can be considered as a solid water layer with atmospheric pressure above and vapour pressure below and it very soon falls back towards the main bulk of water. The closure of the gap results in a pulse generated in a water hammer manner.

Experimental measurements of this surface reloading pulse have been taken and a typical record is shown in figure (5). Sound ranging on the pulses have shown them to originate near the sea surface and their time of occurrence agrees reasonably well with theoretical expectations of the motion of the water above the cavitation gap. The phenomenon may be expected to be complicated by the reflection of the remainder of the shock waves at the first cavitation gap causing a second cavitation gap and so on.

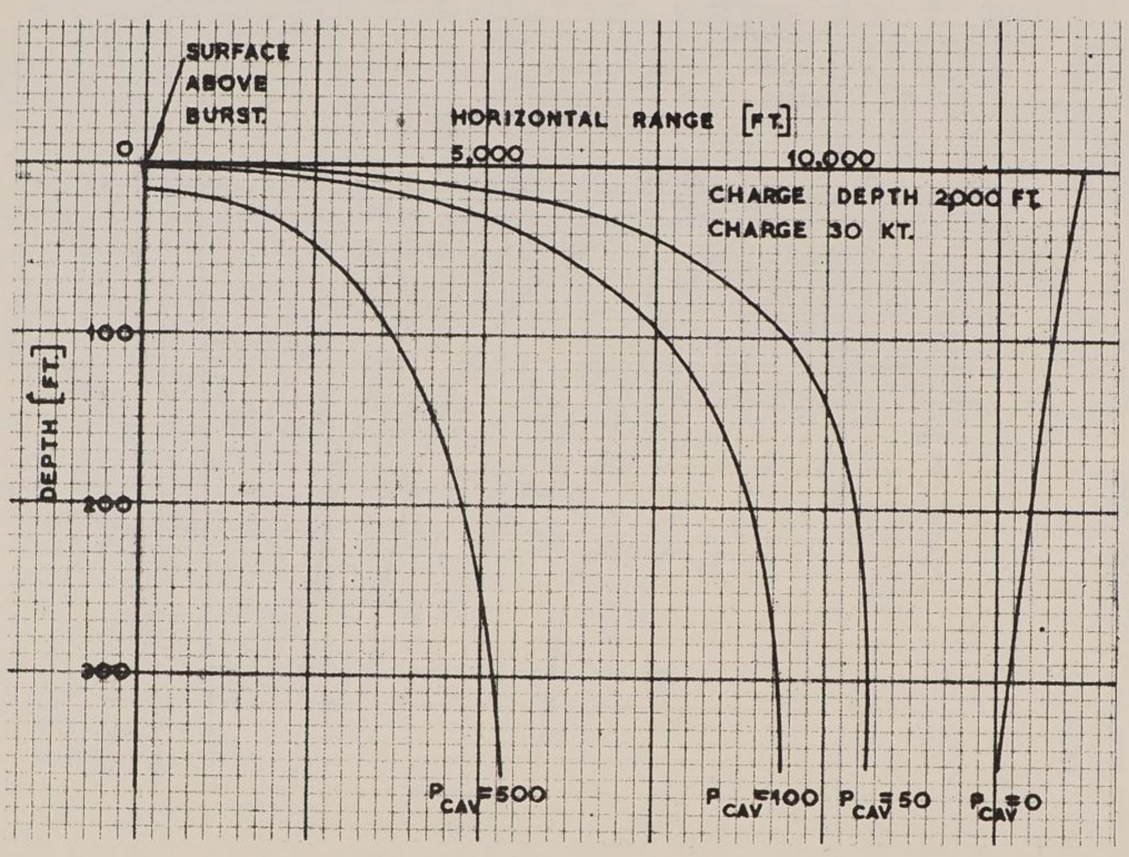
It is clear that the finite breaking tension of sea water can have the effect of converting some of the reflected tension wave into a reflected compression wave. This compression wave may be capable of damaging submerged submarines and this may counteract to some extent the benefit of shallow submergence to be expected purely on cut-off considerations.

Rather little is known about surface reloading pulses, but the present consensus of opinion seems to be that they are unlikely to be serious damaging agents for submerged submarines. Doubts about the scaling laws for surface reloading phenomena make the interpretation of small scale experiments difficult at present.

For References see end of chapter.



CAVITATION SURFACES



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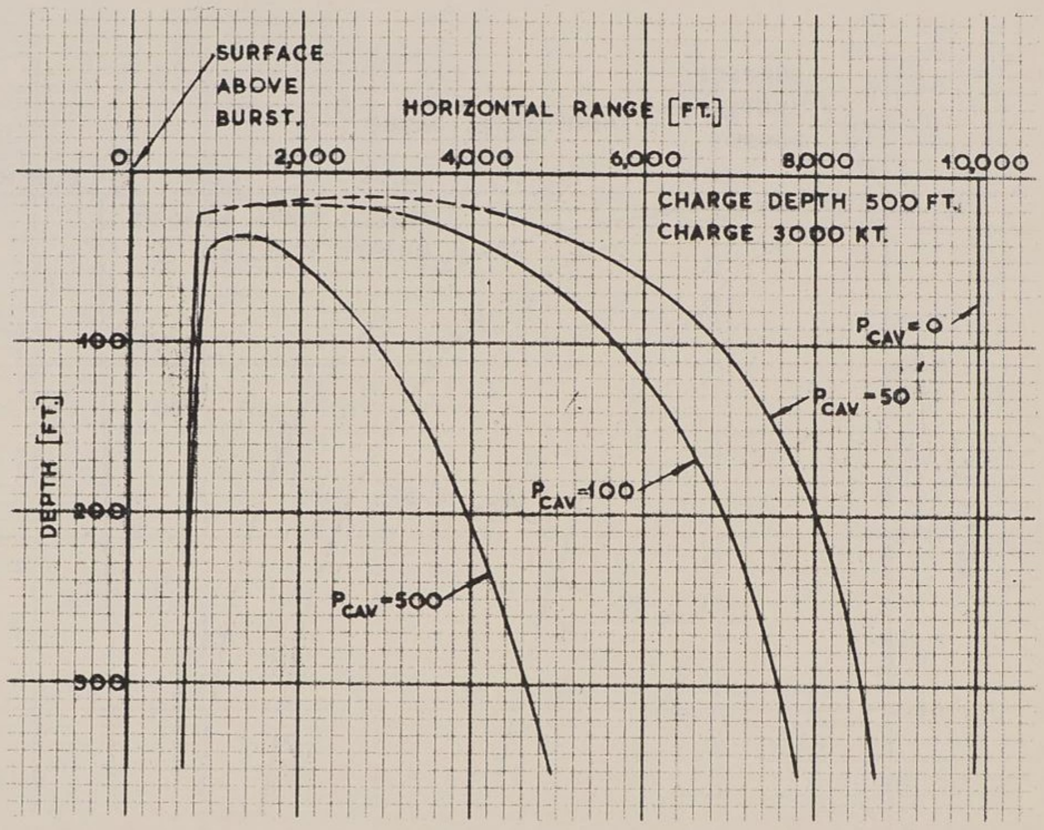

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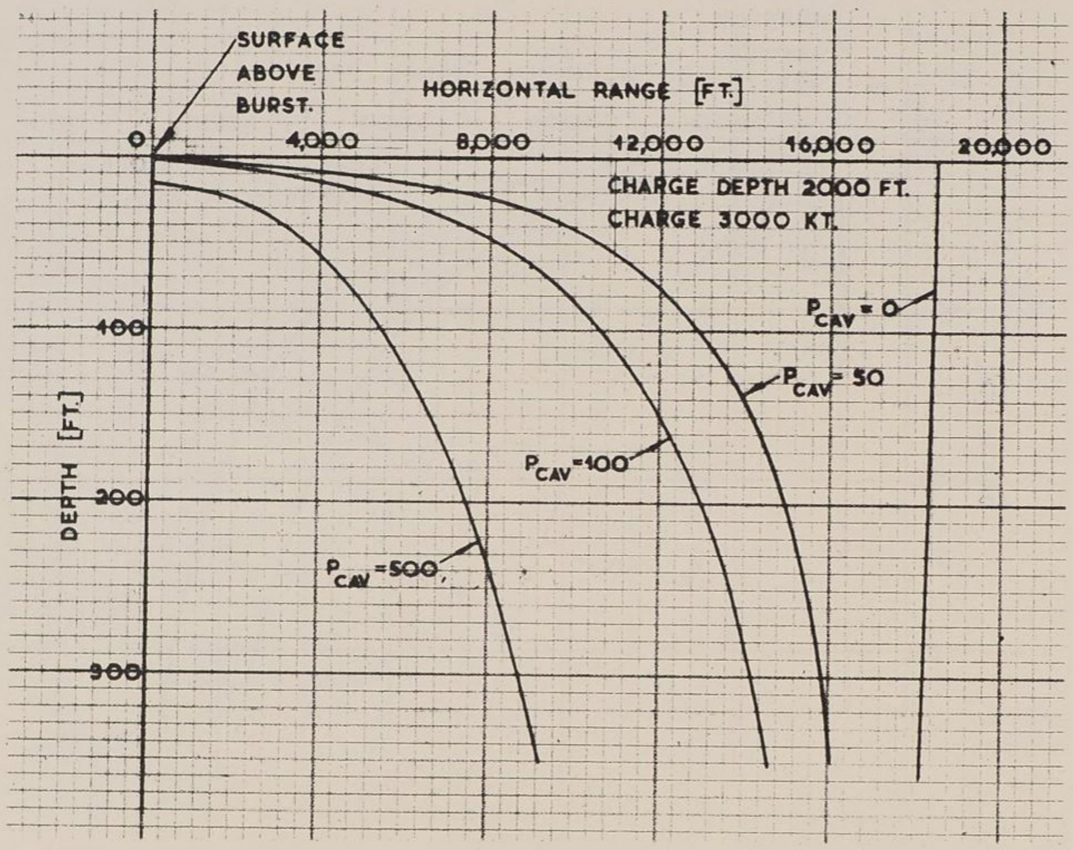

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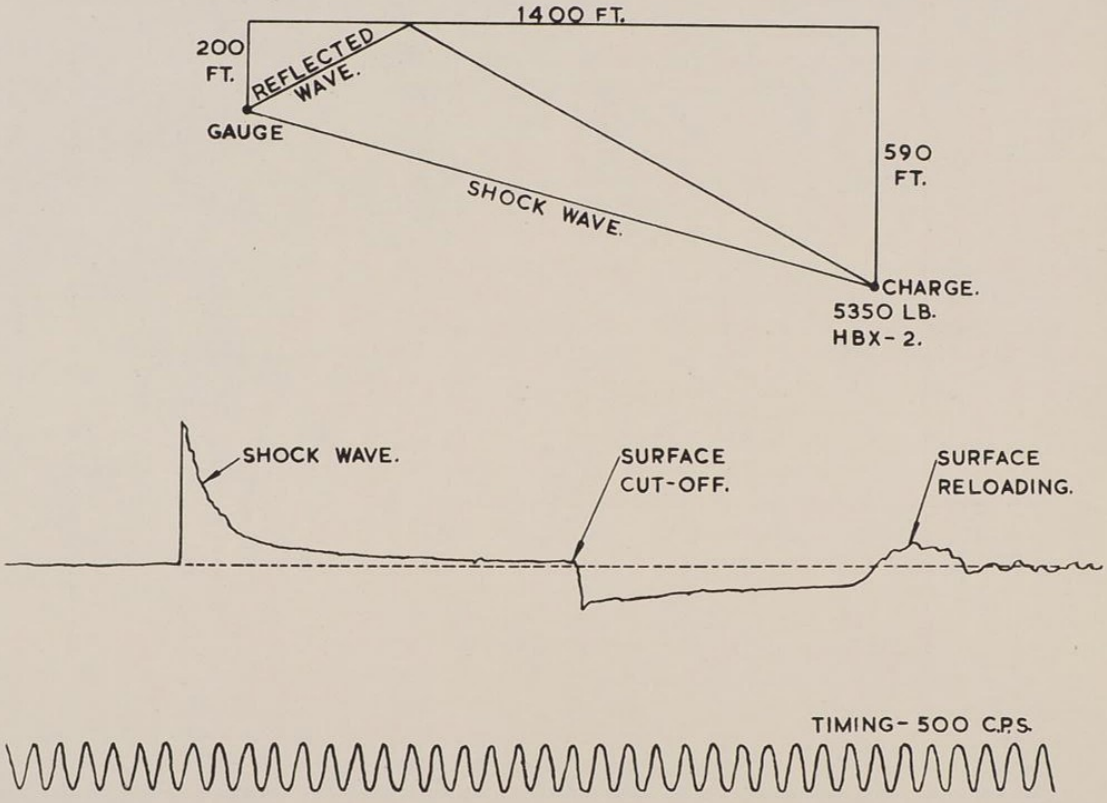

MEASUREMENT OF SURFACE
RELOADING PULSE

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January, 1959

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Chapter 4
Section 4.10

4.10 The Effect of Refraction

The values for lethal radius for megaton weapons given in Table (1) Section 4.8 show that the variation of lethal radii with charge weights for a given burst depth is appreciably less than $W^{1/3}$. This is due to the effect of surface cut-off. If the charge depth could be increased as $W^{1/3}$ the lethal ranges would then increase nearly as $W^{1/3}$ on going from kiloton to megaton weapons but this would involve very large charge depths.

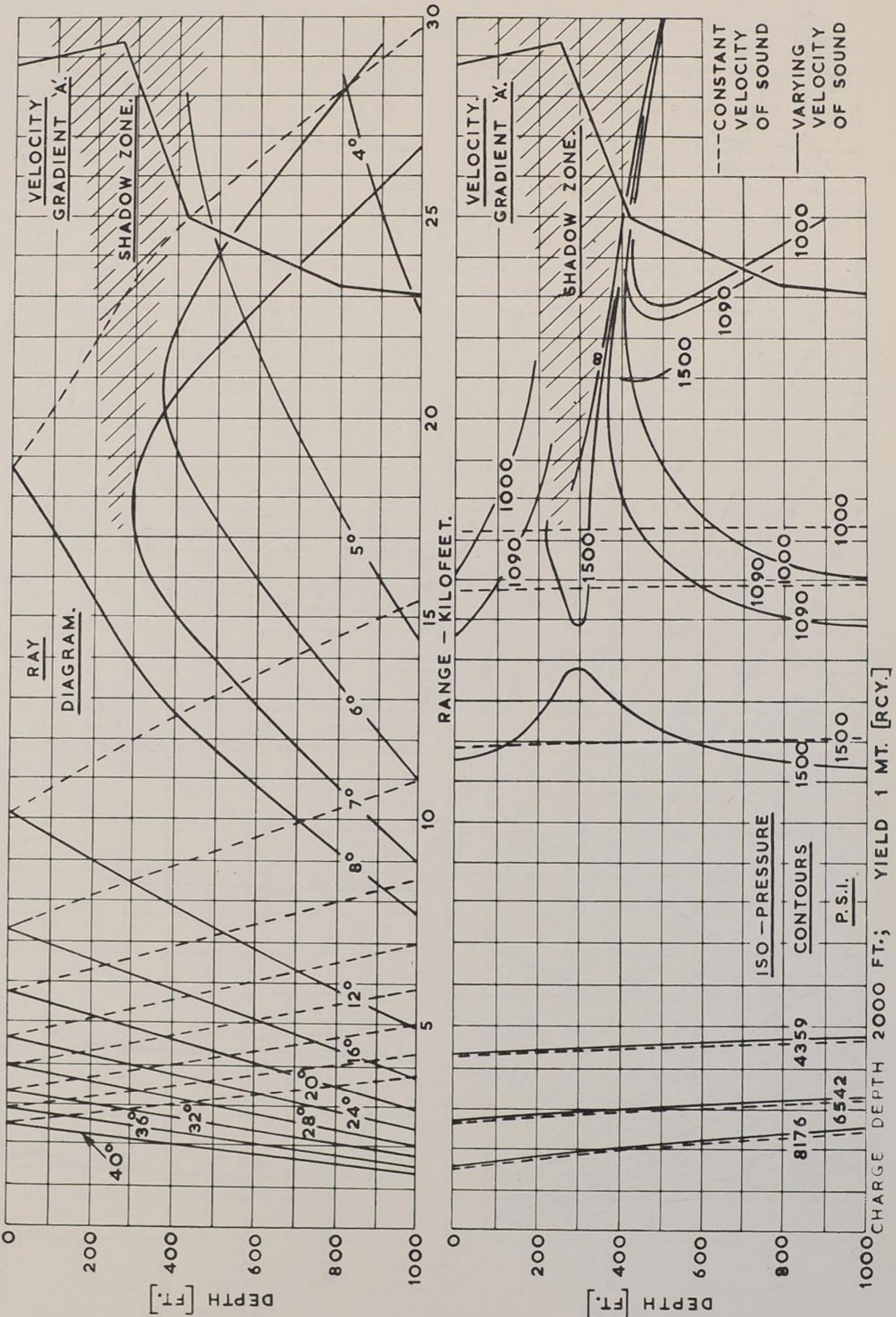
In spite of this effect of cut-off, the lethal radii for megaton weapons are very large, in fact so large that a phenomenon not so far considered can be expected to play a dominating role. This is the phenomenon of refraction due to the non-uniformity of the temperature and salinity of the sea.

In many areas of the oceans the temperature and salinity vary with depth sufficiently to cause changes in the velocity of sound of 1 or 2 per cent over a depth of 2000 ft. The shock front of an explosion wave can be considered to propagate, at the local velocity of sound, along rays which in isovelocity water spread out radially from the explosion source, but which get bent in a medium of varying sound velocity. The rays always take the path shortest in time between any two points, so that when the velocity of sound decreases with depth the rays are bent downwards, and vice versa. This bending of the rays affects the intensity of the shock front; diverging rays reducing the intensity, converging rays increasing the intensity. Thus regions could exist where no rays penetrated. These regions are called shadow zones, and on ray theory they are zones of zero shock wave pressure. In fact, however, the tail of the shock wave does not propagate strictly according to ray theory, and some diffraction of the shock wave into the shadow zone always occurs.

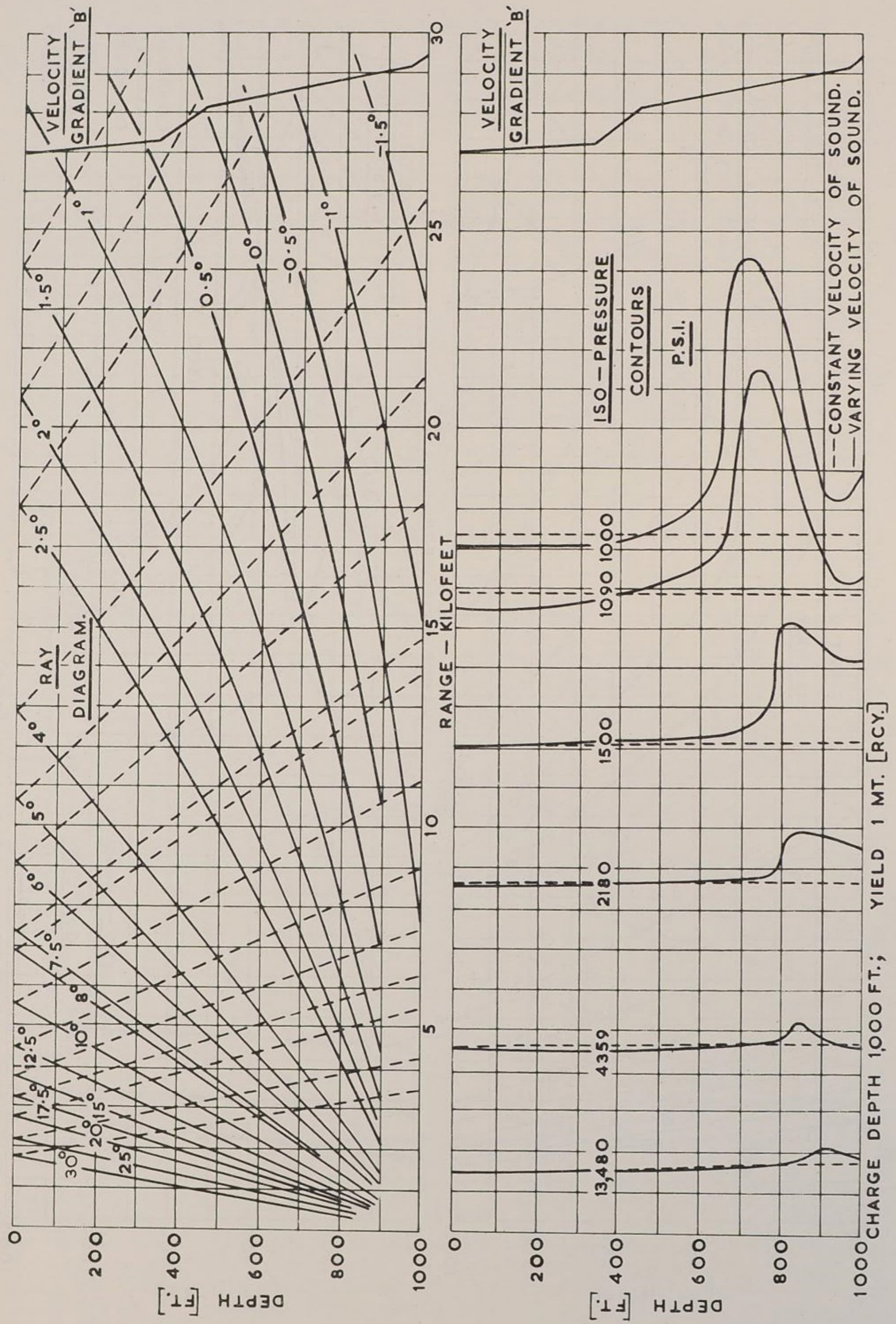
The refraction effect is, to the accuracy of ray theory, purely a function of range and not of charge weight. For conventional H.E. charges the ranges of interest are too small for any significant refraction to take place. For atomic explosions up to 20 KT the effect of refraction is not expected to have a great influence on lethal radii except in special cases. For megaton weapons, however, the ranges of interest are such that refraction effects can be expected to predominate, and the results of Table (1) Section 4.8 are unlikely to hold except as very rough average values that can be far out in specific cases.

To illustrate this fact, the results of ray calculations for March and November near Bermuda are shown in figures (1), and (2). The ray diagrams (taken from Reference 11) show the degree of ray bending that occurs for two particular velocity gradients and depths of burst, as specified in figure 3. These ray diagrams are independent of charge weight. Of more direct interest are the contours of constant shock wave peak overpressure for 1 megaton of T.N.T. These contours can be seen to differ appreciably from the isovelocity contours (circles).

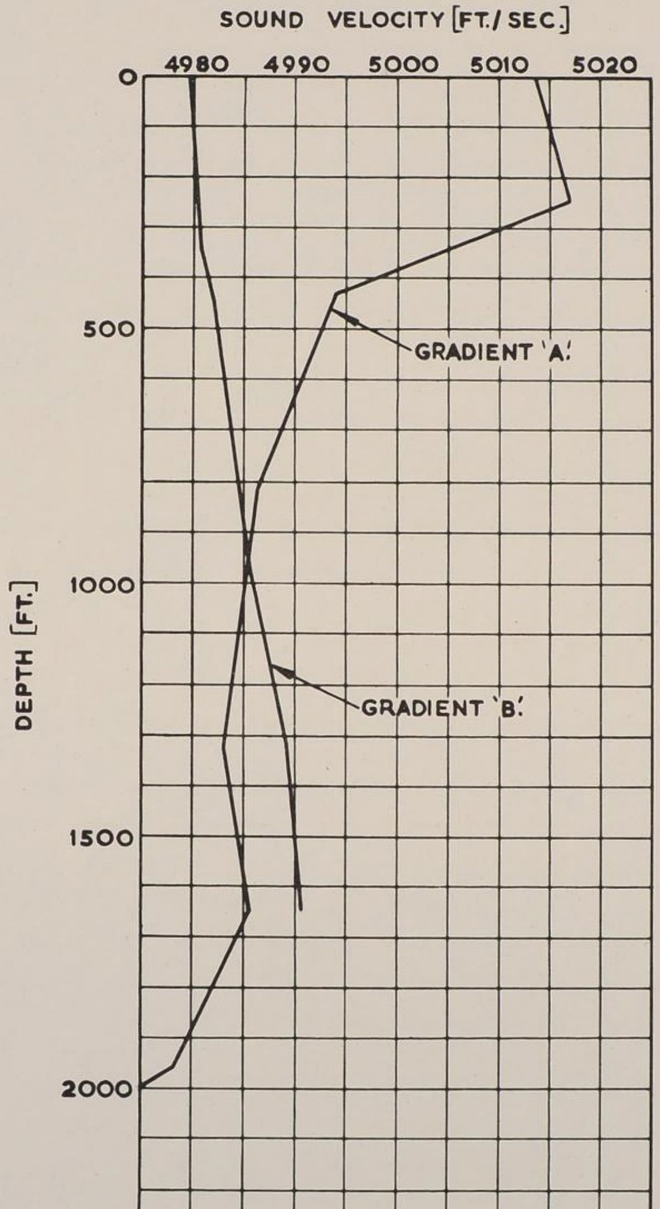
Ray theory is fairly simple to compute, but it can give no indication of pressure time histories. To improve on ray theory sufficiently to enable pressure time histories to be calculated appears to be very difficult, and much theoretical and experimental work will be necessary before this is possible. For this reason calculation of lethal radii under refractive conditions is not at present possible. When the pressure pulse is known, however, all three lethality criteria discussed above - delayed yield, excess energy and excess impulse can be adapted to assess the likely damage. Experimental work on the refraction of underwater shock waves is being carried out at N.C.R.E. Some references are given at the end of this chapter.



REFRACTION OF UNDERWATER SHOCK WAVE,
1 MT BURST AT 2,000 FT. DEPTH.



REFRACTION OF UNDERWATER SHOCK WAVE,
1 MT BURST AT 1,000 FT. DEPTH

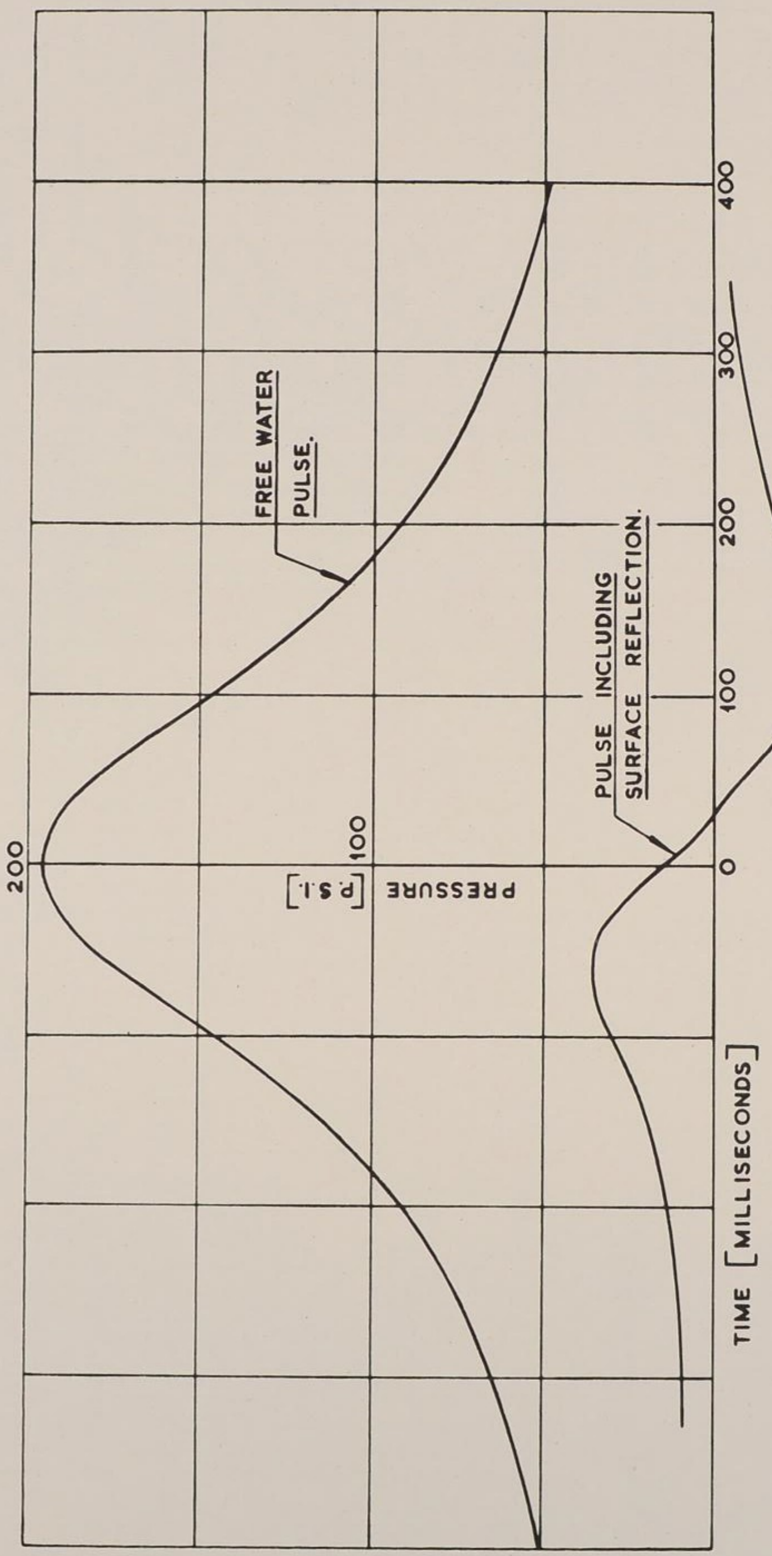


VARIATION OF SOUND VELOCITY
WITH DEPTH

4.11 The Effect of Bubble Pulses

When conventional high explosive depth charges are used to attack submarines the lethal stand-off is usually of the order of 20 ft. at which distance the peak shock wave pressure is 5000 p.s.i. or more. The bubble pulse pressures are likely to be only about 1/10th of this value but the duration is longer than that of the shock wave and 500 p.s.i. is capable of damaging most submarines. Thus the bubble pulse can and usually does cause damage for high explosive attack.

The position is quite different for atomic weapon attack since the peak shock wave pressures at lethal stand-off's are unlikely to exceed 2000 p.s.i. The bubble pulse peak pressure in free water cannot exceed 1/7th of this value, i.e. 300 p.s.i. and this pressure could scarcely damage a modern submarine even if reflection from the free surface was absent. In fact, however, the effect of surface reflection will always be to reduce the peak bubble pressure for free water to much smaller values. This is illustrated in figure (1) where the first bubble pulse, in free water, 3000 ft. from a 23 KT charge exploded 2000 ft. deep is given. Also given is the pulse experienced at 500 ft. submergence when surface reflection is taken into account. The latter pulse is obviously too feeble to have any significance. This conclusion remains generally valid for all larger weapons. If a submarine were almost directly over a very deep explosion, vertical migration could conceivably bring the pulsating bubble near enough to do damage. This would be a strange way to attack a submarine. In the case of surface ships the nearness of the pulsating bubble would almost certainly imply a greater danger from radiation when the bubble breaks surface than from the actual bubble pulse.



FREEWATER BUBBLE PULSE, 3,000 FT. FROM 23 KT
EXPLODED AT 2,000 FT. DEPTH

D1/57
January, 1959

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4.12 Shock Damage to Submarines

The problem of shock to machinery etc. is likely to depend considerably upon the orientation of the attack. For end-on attack and ranges greater than the hull splitting range, little shock damage is likely. For side-on attack two effects are likely to predominate -

(a) Local hull motions along the generator line nearest to the point of explosion

(b) Rigid body motion of the entire submarine cross section.

There is little doubt that the shock problem will usually be less with atomic weapons than with conventional high explosive weapons. This is because the peak pressures at the hull splitting stand-offs are always less for atomic weapons. Thus if, as is attempted, all submarine equipment were successfully designed to resist the shock at hull splitting stand offs for high explosive weapons, there would be no shock problem for atomic weapons. In fact, however, it is unlikely that any submarine designed to date achieves this ideal, and shock is likely to be a significant problem under attack by atomic weapons, although possibly only for shallow submarines.

(a) Local Hull Motions

Points facing the explosion can be expected to acquire velocities close to $2P_m/\rho c$ (see Section 3.5). This velocity has been evaluated for the cases given in Table (I), Section (4.8) and the results are given in Table I below -

TABLE I

Yield W (kilotons)	Collapse Pressure (p.s.i.)	Charge Depth (feet)	Submarine Depth (feet)	Slant Range (Hull Splitting) (ft.)	Peak Pressure (p.s.i.)	$\frac{2P_m}{\rho c}$ (ft./sec.)
1.5 KT	500	500	50	1810	1063	30.6
"	"	"	500	2670	685	19.7
"	"	2000	50	1920	990	28.4
"	"	"	500	2670	685	19.7
30 KT	"	500	50	3900	1380	39.6
"	"	"	500	8970	538	15.5
"	"	2000	50	4900	1070	30.7
"	"	"	500	9740	491	14.1
30,000 KT	"	500	50	15800	3832	110
"	"	"	500	43700	1210	35
"	"	2000	50	25800	2210	63.5
"	"	"	500	73500	67.5	19.4
30 KT	670	500	50	3190	1730	49.1
"	"	"	500	6330	792	22.8
"	"	2000	50	4610	1138	32.6
"	"	"	500	6410	785	22.5

There is a considerable doubt about the value of local hull velocity required to cause serious shock damage. This is rather inevitable since the answer depends upon the degree of "shock-consciousness" of the designers of the equipment. Ideally a submarine should be capable of withstanding plating velocities of about 60 ft./sec. In fact a value of about 35 ft./sec. for plating velocity is likely to lead to serious damage in most submarines.

(b) Rigid Body Motion

The motions of the entire submarine cross section can be calculated to a first approximation as the response of a circular cylinder of neutral buoyancy. This response is only a function of the parameter $\beta a/c$ where $(1/\beta)$ is the time constant of the shock wave $\left(P = P_{m}e^{-\beta t}\right)$

a is the radius of the cylinder
c is the velocity of sound

Figure (1) gives the response for a wide range of the parameter $\beta a/c$.

For any particular attack geometry $\beta a/c$, $P_m/\rho c$ and a/c are known and multiplying the appropriate curve (or an interpolated curve) of figure (1) by $(P_m/\rho c)$ for the ordinate and a/c for the abscissa gives the resultant rigid body velocity in free water in the direction of propagation of the shock wave. The effect of cut-off can easily be obtained by superposition, as follows:-

First plot the vertical and horizontal components of the resultant rigid body velocity in free water. These are just $\sin\alpha$ and $\cos\alpha$ times the resultant velocity respectively (figure 2). Then plot on the same graphs the vertical and horizontal components of the resultant velocity obtained from the image charge delayed by a time equal to the cut-off time. The sum of the velocity produced by the charge and the image charge give the velocity histories under the influence of cut-off. For a typical set of velocity curves see figures (2) and (3).

Experimental measurements of bodily velocities tend to give appreciably higher values than those calculated for a neutrally buoyant rigid cylinder. This is possible because the outer hull weight of submarine is only a fairly small percentage of the total weight. Thus the outer hull, which responds before the machinery etc. inside can do so, can acquire bodily velocities higher than the average. This means that vibrations can be set up with momentary velocity of individual items appreciably greater than the average. The maximum velocity that can be achieved in this way is twice that for a neutrally buoyant rigid cylinder.

A typical bulkhead velocity recording taken from reference 10 is shown in figure (4), where the theoretical curve is included for comparison. The experimental maximum velocity is seen to be about 75% greater than the theoretical.

In spite of this increase of experimental over theoretical rigid body velocities, the maximum rigid body velocity will always be less than, or just possibly equal to, the local hull velocity treated in (a) above. This does not necessarily mean, however, that the shock problem due to local hull velocity will always be the greater, since many an item in a submarine can be expected to be more sensitive to say 15 ft./sec. applied directly to itself, than to say 30 ft./sec. applied at the hull - leading to considerably less at the item. There is even a possibility that the large horizontal bodily velocities that can be experienced under atomic attack constitute a new shock problem that is not important for conventional attack.

Probably the best guess that can be made at present is that 10 ft/sec. horizontal and 20 ft/sec. vertical bodily velocities, give about the limit of serious shock damage. Bearing in mind the increase of experimental over theoretical values this suggests theoretical limiting values of about 8 and 15ft./sec. for horizontal and vertical velocities respectively.

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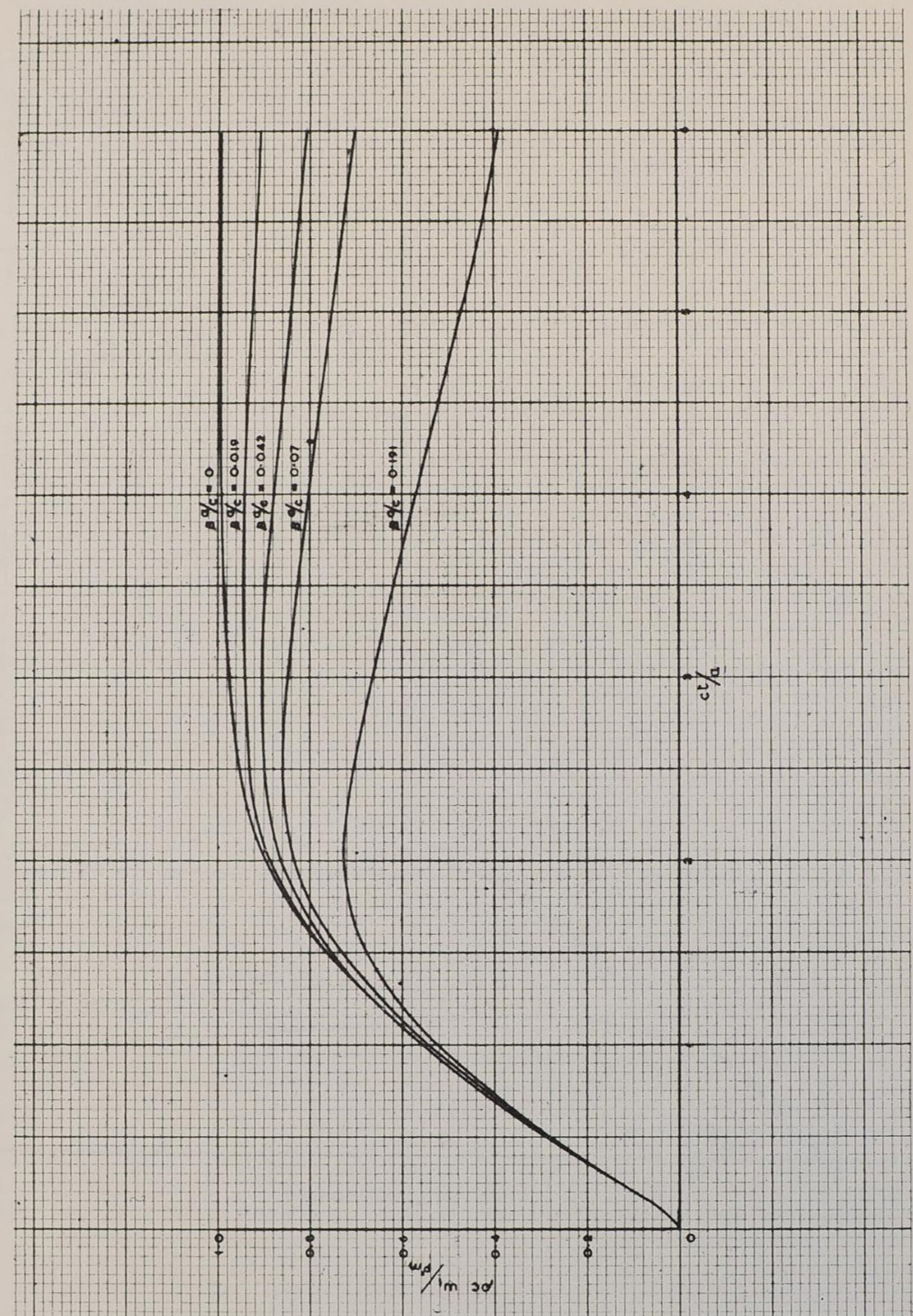
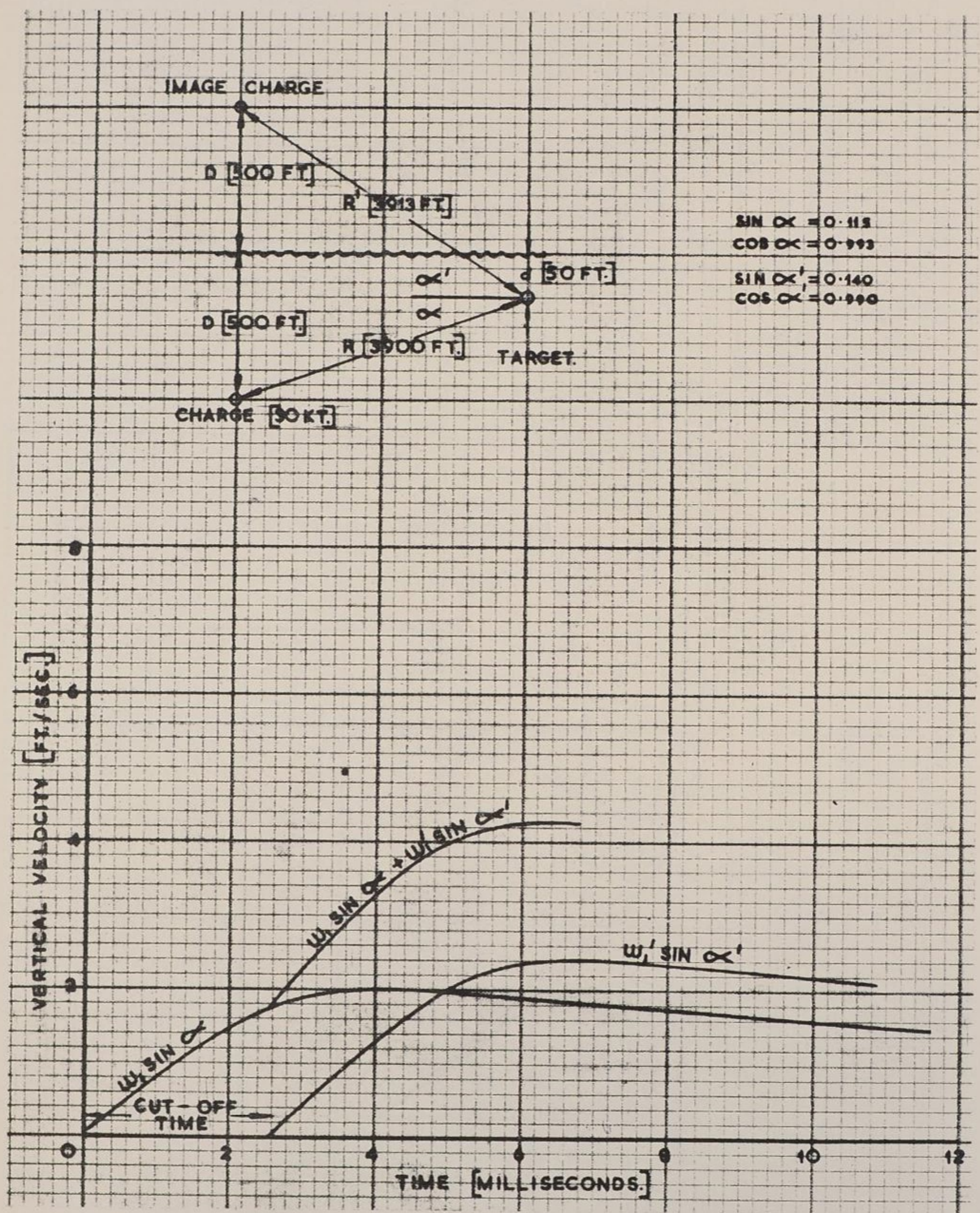


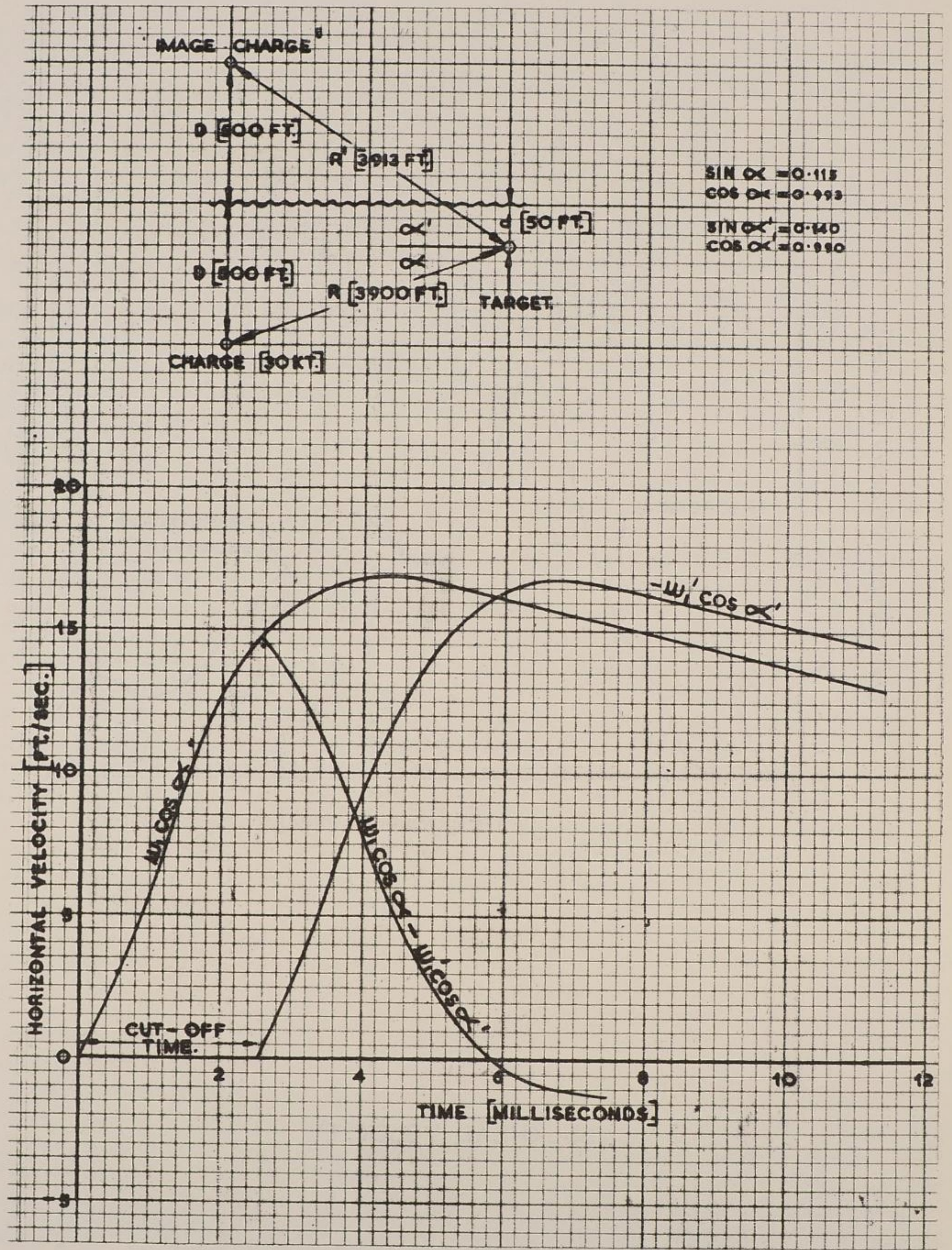
THE RESPONSE OF A CIRCULAR CYLINDER
OF NEUTRAL BUOYANCY

CONFIDENTIAL

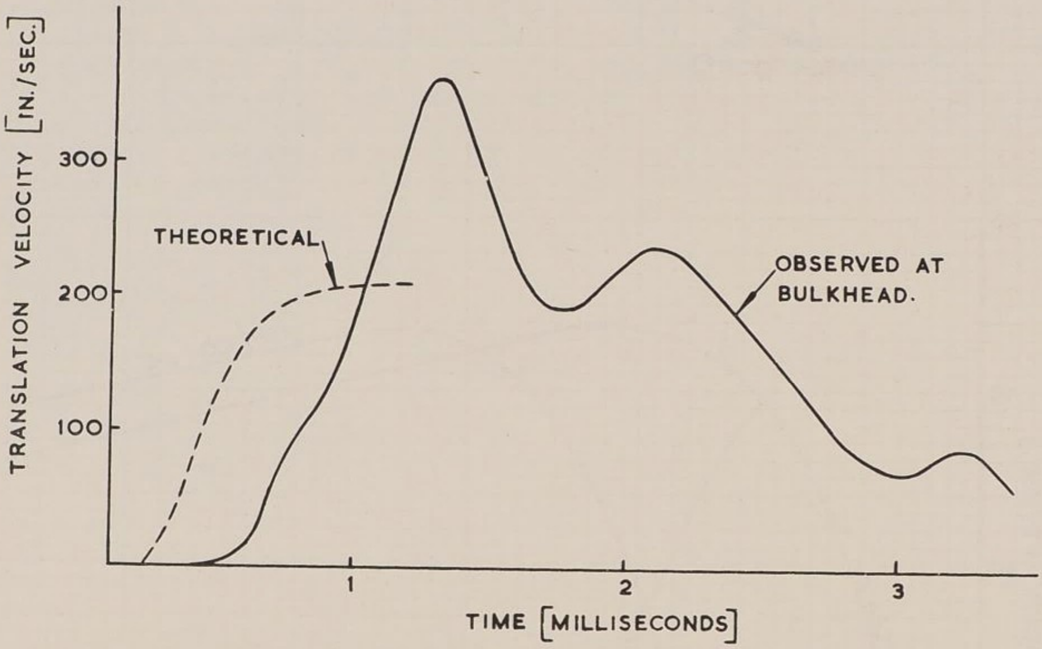


RIGID BODY VERTICAL MOTION

CONFIDENTIAL



RIGID BODY HORIZONTAL MOTION



BULKHEAD VELOCITY

CHAPTER 5 - OTHER SUBMERGED STRUCTURES

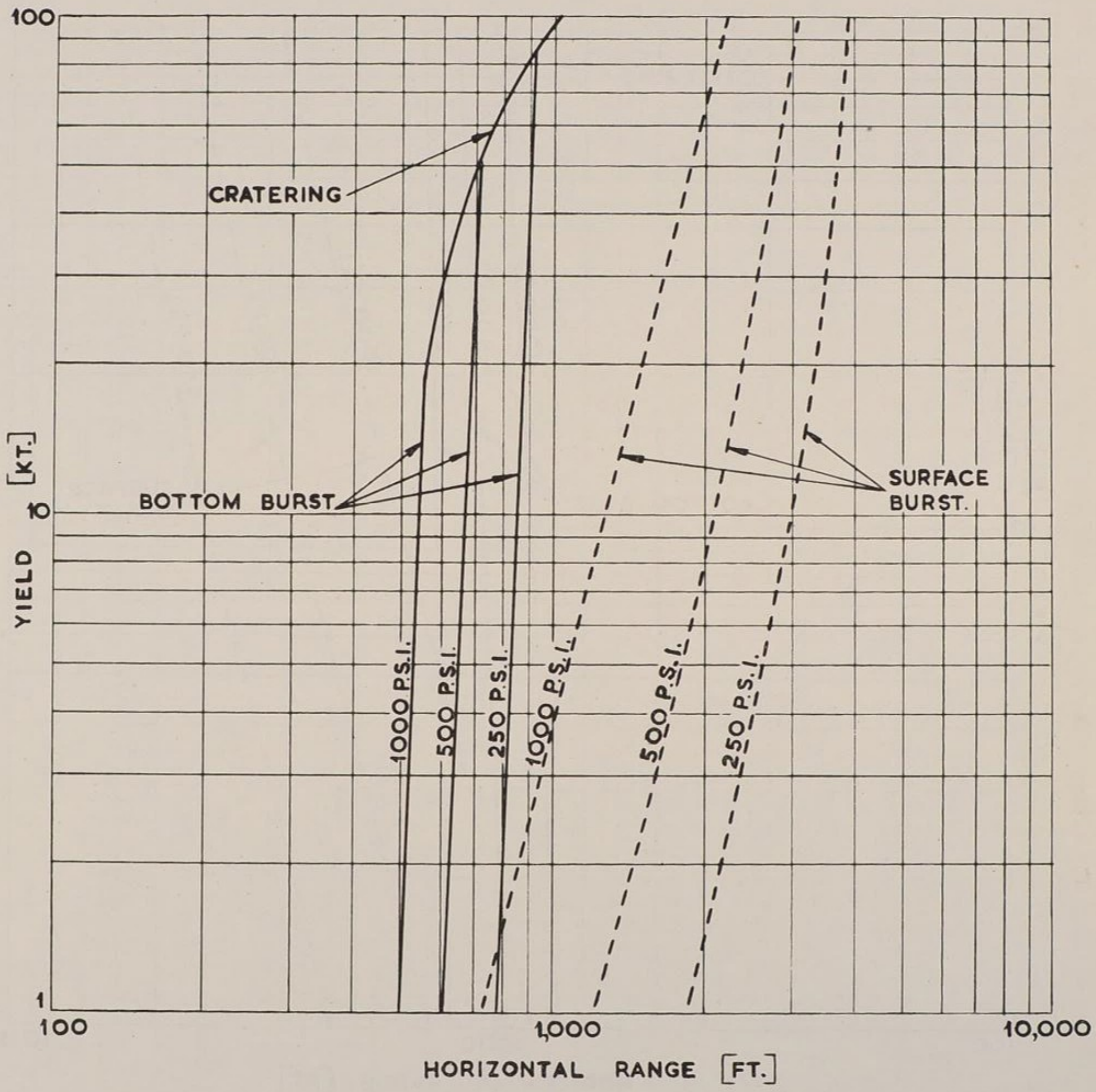
5.1 Introduction

Ships are the most important but are not the only structures susceptible to underwater explosions. Mines, Lock Gates, Underwater pipe lines etc., will usually be far more vulnerable to underwater than to airburst attack. Due to their smaller importance no experimental work has been carried out on the response of these items to underwater atomic attack. For this reason the damage criteria given in this chapter are inevitably based on a combination of theory and comparison with ships structure.

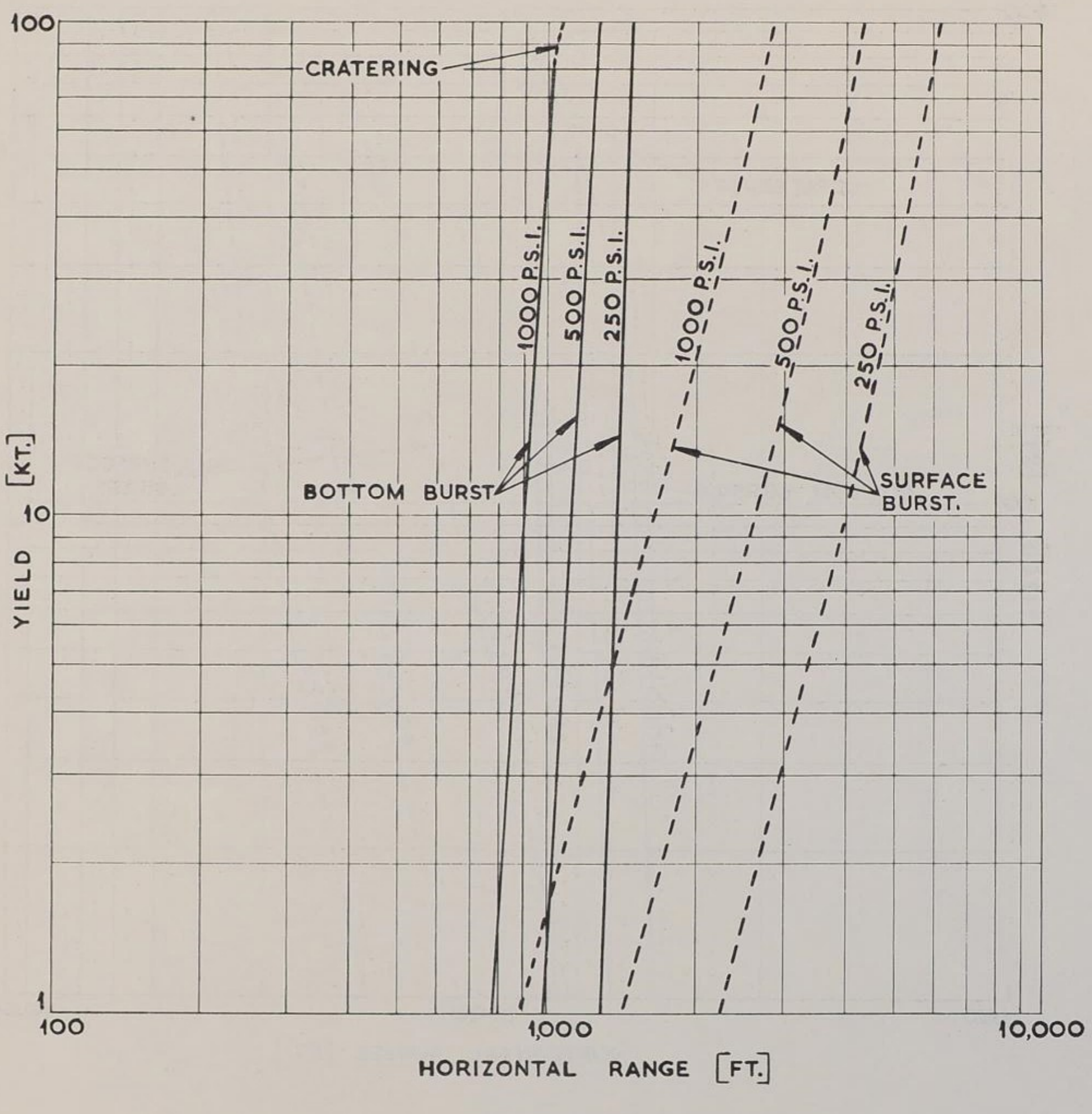
5.2 Mine Neutralisation

Structurally, a mine case is reasonably similar to a submarine but is always of considerably smaller size. For this reason it is to be expected that damage sufficient to cause mine neutralisation will result when the peak shock wave pressure exceeds the static collapse pressure of the mine case by a small margin. Reference (1) assumes that a peak pressure equal to the static collapse pressure will cause neutralisation and presents neutralisation curves for burst and mines on the bottom. These curves are very difficult to verify since the shallowness of the bursts of interest results in the underwater shock wave being very much affected by non-linear surface reflection (see Chapter 1).

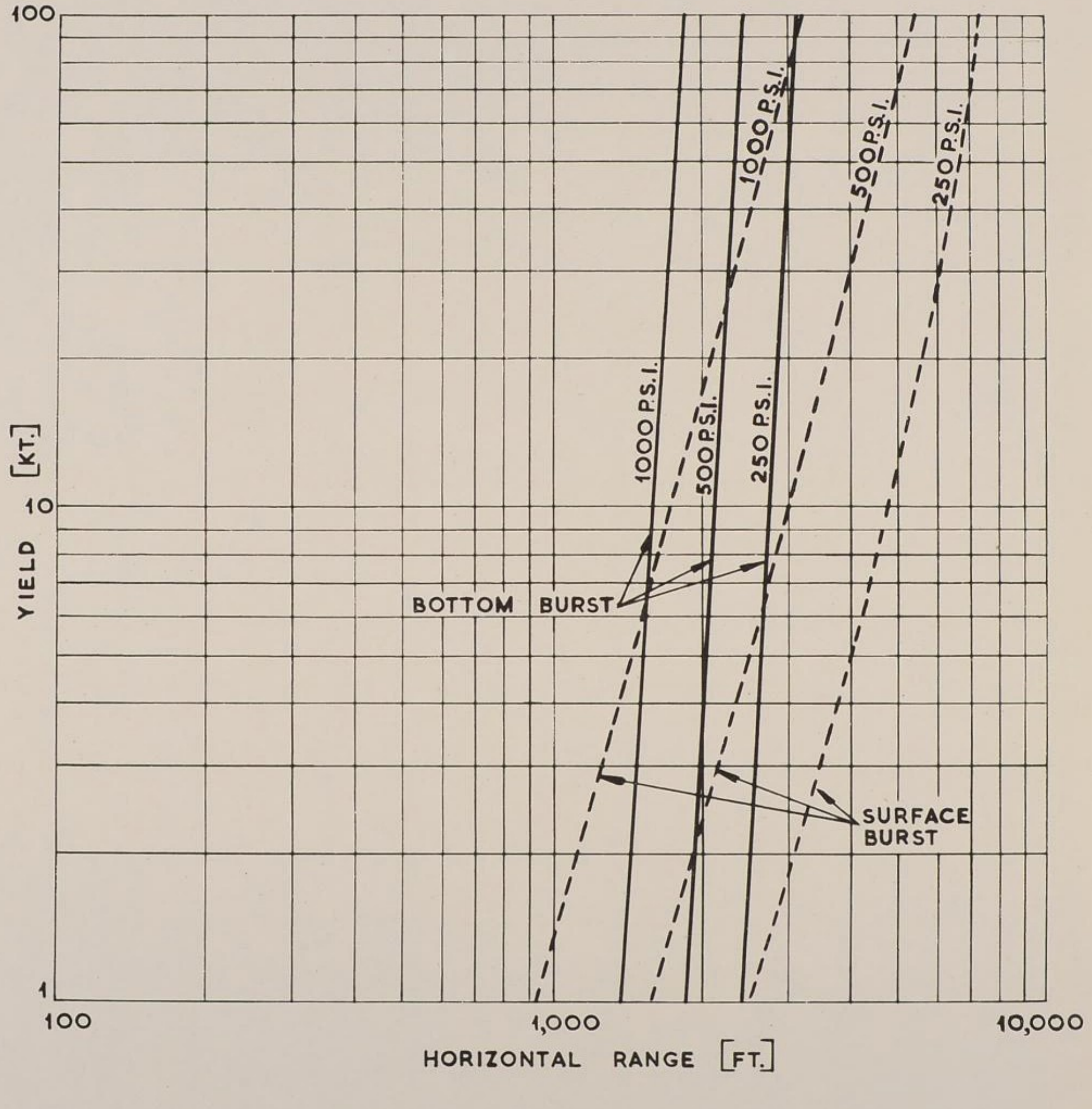
The ranges at which collapse pressures of 250, 500 and 1,000 p.s.i. are reached, neglecting the presence of the bottom and using the only available theory of non-linear surface reflection (Data sheet 4.4 of the "Manual on the Effects of Atomic Weapons") and more than 3 times as great as those given by the curves in Capabilities. This suggests that the ranges given in Capabilities may be much too small but some allowance may have to be made for the so-called "shadow-band" effect. This is the name given to the rather curious effect that with explosions on the sea bed the peak pressures at given distances are lower adjacent to the sea bed than at greater elevations. This effect has been found in the region with an elevation less than about 10° above the burst and very limited evidence suggests that the peak shock wave pressures can be reduced to about 50% of the free water value. For this reason there is considerable doubt about the pressure distribution along the bottom with a bottom burst and the curves of Capabilities are reproduced in figures 1, 2 and 3 together with the curves for a burst in the surface calculated from figure 4.4.5 of the "Manual on the Effects of Atomic Weapons". These curves need to be treated with considerable reserve.



UNDERWATER MINEFIELD NEUTRALISATION,
50FT. DEPTH OF WATER, MINES ON BOTTOM



UNDERWATER MINEFIELD NEUTRALISATION,
100FT. DEPTH OF WATER, MINES ON BOTTOM



UNDERWATER MINEFIELD NEUTRALISATION,
200 FT. DEPTH OF WATER, MINES ON BOTTOM

5.3 Underwater Pipe Lines

Pipe lines that are completely filled with liquid are unlikely to be damaged unless within the crater. Gas filled pipe lines will be destroyed when the peak shock pressure exceeds the static collapse pressure by a small margin and the curves of figures 1, 2, 3 of Section 5.2 are applicable.

Pipes which are only partially filled with fluid will be collapsed on to the fluid at the destruction range for gas filled pipe lines. This may or may not lead to rupture depending on the proportion of liquid filled volume, ductility etc.

5.4 Dock Gates

The vulnerability of Dock Gates to underwater attack can be expected to be very sensitive to the height of water on both sides of the gate and to the type of gate. A gate of solid construction with the water level on the attacked side no higher than on the other side will be very little affected by the underwater shock at ranges where the surface waves would probably cause serious damage. For the same gate with the water level on the attacked side say 20 ft. higher than on the other side, the underwater shock can be expected to be the most important damaging agent unless the surface waves are increased by focussing, shelving bottom etc. In the latter case neglecting wave actions, the energy parameter E_H (Section 3.4) should give a fairly reliable damaging criterion with a value $E_H = 5.10^4$ ft./lb./ft.^{2} leading to rupture.

Dock Gates of watertight "egg box" construction can be expected to behave as ships' sides regardless of the relative heights of the water on the two sides. Damage leading to rupture could be expected on the attacked side when $E_H = 5.10^4$ ft.lb./ft.^{2} and this may or may not affect the operation of the gate depending upon the detail design. The side not attacked, if water backed, could be expected to be difficult to rupture, but the gate would probably be inoperable, although possibly still fairly watertight, long before rupturing stand-off is reached.

5.5 Dams

Concrete dams are likely to be more vulnerable to underwater shock than to airblast when the water level is higher than about half dam height. As the depth of water increases the vulnerability of the dam to an underwater burst increases. This is partly due to the increased static loading but is mainly due to the increased pressure pulse durations with deeper water. The great mass of dams makes it likely that damage will be governed by impulses rather than energy. This is assumed in Reference (1) where the following damage estimates are given for full concrete gravity dams (straight or slightly curved in plan) for a 20 K.T. underwater burst.

60 ft. high dam

Cracks are produced at a range of about 300 yds. Portions are cracked loose and displaced small distances at a range of about 200 yds.

150 ft. high dam

Cracks are produced at a range of about 500 yds. Portions are cracked loose and displaced sizeable distances at a range of about 200 yds.

500 ft. high dam

Cracks are produced at a range of about 1,300 yds. Portions are cracked loose and displaced large distances at a range of about 200 yds.

These estimates for cracking correspond to impulse values at the mean height facing the charge of 2.4, 4.7 and 6.5 p.s.i. seconds for 60, 150 and 500 ft. high dams respectively.

The cracking loose estimates correspond to impulse values at the same position of approximately 5.7, 32, 170 p.s.i. seconds for 60, 1,500 and 500 ft. high dam respectively.

5.6 Wave Damage

The question of wave damage to dock gates or indeed to any harbour installation requires an individual analysis of each target. The variables involved are water depth, bottom slope, wave height, wave length, target response characteristics, orientation of target to wave front, location of target relative to the point of wave breaking and variation in width of the channel or harbour.

The estimation of water height in water of uniform depth is treated in Data Sheet 4.11 of the Manual on the Effects of Atomic Weapons. Further curves of estimated wave heights reproduced from "Capabilities" are given in figure 1. These latter curves do not entirely agree with the data given in M.E.A.W. and the disagreement reflects the degree of ignorance on this problem.

An example of the types of problem that arise is given by considering the effect of a 20 K.T. underwater explosion in the Bristol Channel. Provided this is carried out at least 20 miles from land in a favourable wind the problems arising from airblast, thermal, gamma radiation or underwater shock would be minor. The wave height reaching the Gower Peninsula and the Devon Coast would be around 2 ft. but the progress of this wave down the Bristol Channel could lead to a magnification of the wave height. The wave height in a slowly narrowing channel is inversely proportional to $(\text{breadth})^{\frac{1}{2}} \times (\text{depth})^{\frac{1}{4}}$, thus the wave height may reach about 30 ft. at Avonmouth and even higher further down the Severn.

This type of consideration may be a limiting factor in the use of atomic depth charges around coasts, and requires study.

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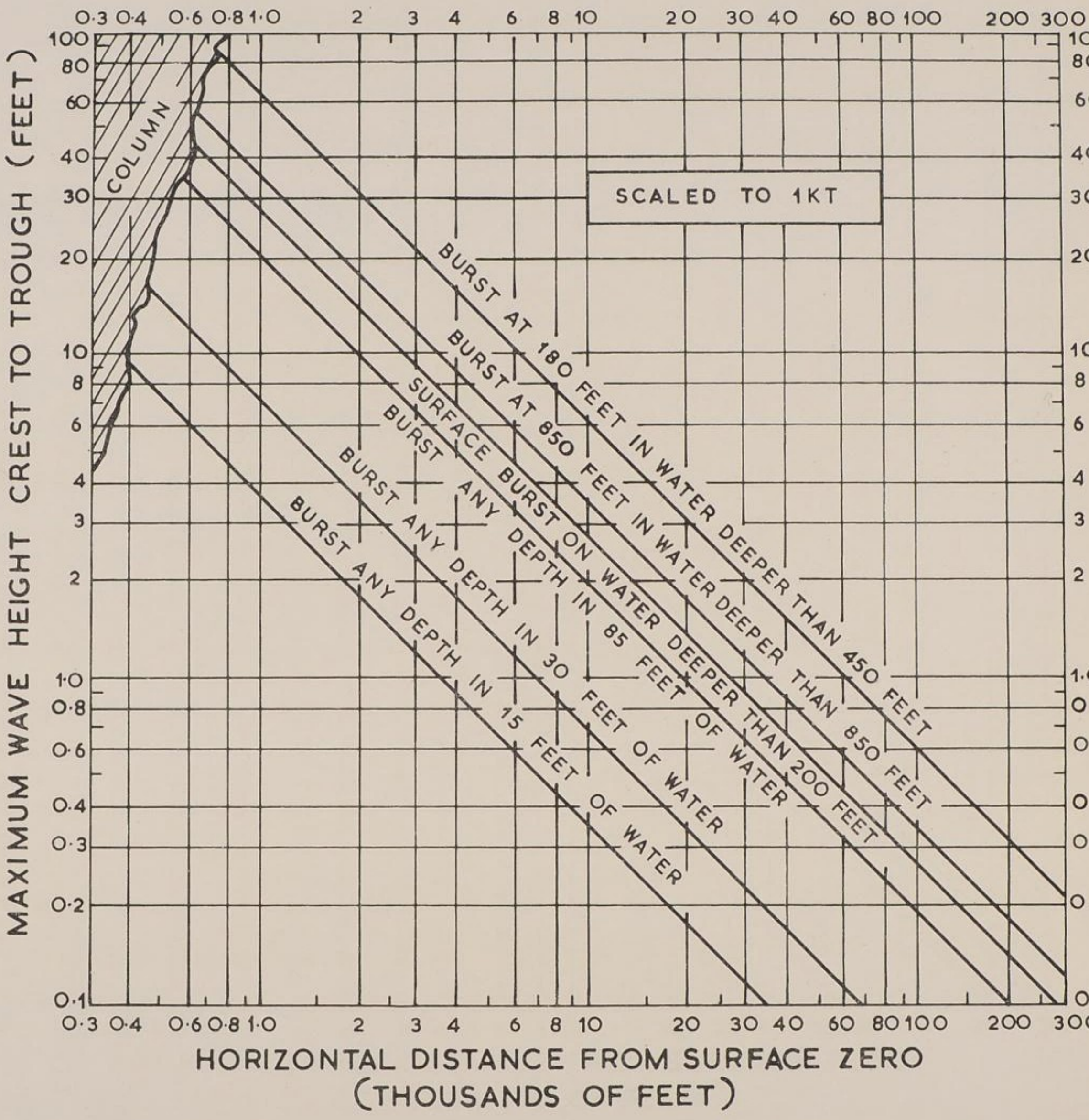

ESTIMATED WAVE HEIGHTS FOR WATER BURSTS

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SYMBOLS

a	Absorptivity
c	Specific heat (cal/gm/°C)
D	Distance of target from energy source (feet)
E	Thermal energy of source (calories)
$\underline{E}$	Young's Modulus (tons/in^2)
$\bar{e}$	Emissivity
g	Absorption coefficient (of thermal radiation, for ground cut-off)
H	Newtonian cooling constant (cal/cm^2/sec/°C)
H'	Heat transfer coefficient for convective cooling from a surface (cal/cm^2/sec/°C)
I	Intensity of incident radiation (cal/cm^2/sec)
K	Thermal conductivity (cal/cm/sec/°C)
k	Thermal diffusivity (cm^2/sec)
l	Half thickness of irradiated material (cm)
p	Radiant power (cal/sec)
p_{max}	Maximum radiant power (cal/sec)
Q	Radiant exposure (cal/cm^2)
q	Heat loss from a surface (cal/cm^2/sec)
R	Radius of fireball (feet)
r	Reflectivity
T	Temperature (°C or as otherwise specified)
$\bar{T}$	Thermal transmittance of the atmosphere
$\bar{t}$	Thermal transmittance of material
t	Time (seconds)
t_{max}	Time to second thermal maximum (seconds)
W	Total weapon yield (kilotons)
x	Distance (within an irradiated material) (cm)
γ	Extinction coefficient (Bougier-Lambert Law)
θ	Temperature rise (°C)
μ	Attenuation coefficient for thermal radiation
ρ	Density (gm/cc)

CHAPTER I - INTRODUCTION

1.1 Characteristics of the Fireball

1.1.1 Formation

Owing to the great heat produced by a nuclear explosion all the materials in the weapon are converted into the gaseous form. Since the gases at the instant of explosion are restricted to the region occupied by the original constituents in the bomb, tremendous pressures are produced. Within a few millionths of a second of the detonation of the bomb the intensely hot gases at extremely high pressure formed in this manner appear as a roughly spherical highly luminous mass. This is the fireball (or ball of fire). Although the brightness decreases with time, after about 0.7 milliseconds the fireball from a 1-megaton nuclear bomb would appear to an observer 60 miles away to be more than thirty times as brilliant as the sun at noon (Reference (1)). As a general rule, the luminosity does not vary greatly with the energy (or yield) of the bomb. The surface temperatures attained, upon which the brightness depends, are thus not very different in spite of differences in the total amounts of energy released.

In the very earliest stages of its formation the temperature throughout the fireball is uniform. The energy produced as a result of fission (and fusion) can travel rapidly as radiation between any two points within the sphere of hot gases, and so there are no appreciable temperature gradients. Because of the uniform temperature the system is referred to as an isothermal sphere which, at this stage, is identical with the fireball.

As the fireball from an air burst grows, a blast wave develops in the air and the shock front at first coincides with the surface of the iso thermal spheres and the fireball. However, when the temperature falls below about 300,000°C the shock front advances more rapidly than the isothermal sphere. As the shock front moves ahead of the isothermal sphere it compresses the air before it to about ten times its normal density and in doing so raises its temperature to a sufficient extent to render it incandescent. The fireball now consists of two concentric regions. The inner (hotter) region is the isothermal sphere of uniform temperature, and this is surrounded by a layer of luminous shock-heated air at a somewhat lower, but still very high temperature. As the shock expands, its temperature continues to fall until a time is reached when the shock is no longer incandescent (the first minimum), and then becomes transparent to the radiation of the hotter internal sphere. From this time the temperature of the visible fireball again rises to a peak (the second maximum), and finally falls as the inner sphere expands and cools. Only a very small proportion of the total thermal energy release of a true air burst occurs before the first minimum. The rest is released during the second or main thermal pulse.

For a surface burst having the same yield as an air burst, the presence of the earth's surface results in a reduced thermal radiation emission and a cooler fireball when viewed from that surface. This is due primarily to heat transfer to the soil or water, the distortion of the fireball by the reflected shock wave, and the partial obscuration of the fireball by dirt and dust (or water) thrown up by the blast wave.

In underground bursts the fireball is obscured by the earth column, and therefore thermal radiation effects are negligible. Nearly all of the thermal radiation is absorbed in fusing and vaporizing the earth.

Thermal radiation from an underwater detonation is increasingly absorbed in vaporization and dissociation of the surrounding medium as the depth of burst is increased. Its direct effects are insignificant for most practical purposes; e.g. for a 20-KT burst ninety feet below the surface of water, thermal effects are negligible. (Reference (2)).

References

(1) Effects of Nuclear Weapons, U.S.A.E.C. (1957) p.19.

(2) Capabilities of Atomic Weapons, U.S. Dept. of the Army, TM 23-200 (1957) p.3 - 1. (Confidential)

1.1.2 Radius of the Fireball

A detailed discussion of the growth of the fireball will be found in M.E.A.W. Data Sheet 3.1.2, and an unclassified account is given in Reference (1).

The maximum size of the luminous fireball may be represented by a scaling law in the form of the equation:-

$$\frac{R}{R_o} = \left(\frac{W}{W_o}\right)^{0.4}$$

where R is the maximum radius of the luminous fireball for a bomb with a total energy yield of W kilotons, and R_o is the (known) value for a reference bomb of W_o kilotons.

By making use of this scaling law, together with the results obtained at various nuclear test explosions, the following relationship may be derived (Reference (1)):-

$$R \text{ (feet)} = 230\ W^{0.4}$$

From this expression the maximum radius of the luminous fireball (in feet) for a bomb energy of W kilotons may be calculated.

The manner in which the radius increases with time, in the period from approximately 0.1 millisecond to 1 second after detonation of a 20-KT nuclear bomb is shown in Figure 1, taken from Reference (2).

The data given above are thought to be reasonably accurate at heights up to 50,000 ft. For bursts at very high altitudes (of the order of 100,000 ft.) it has been estimated that a significant amount of thermal energy will be emitted before the first minimum, and that the radius of the fireball may be three times as great. (Reference M.E.A.W. Data Sheet 3.1.5).

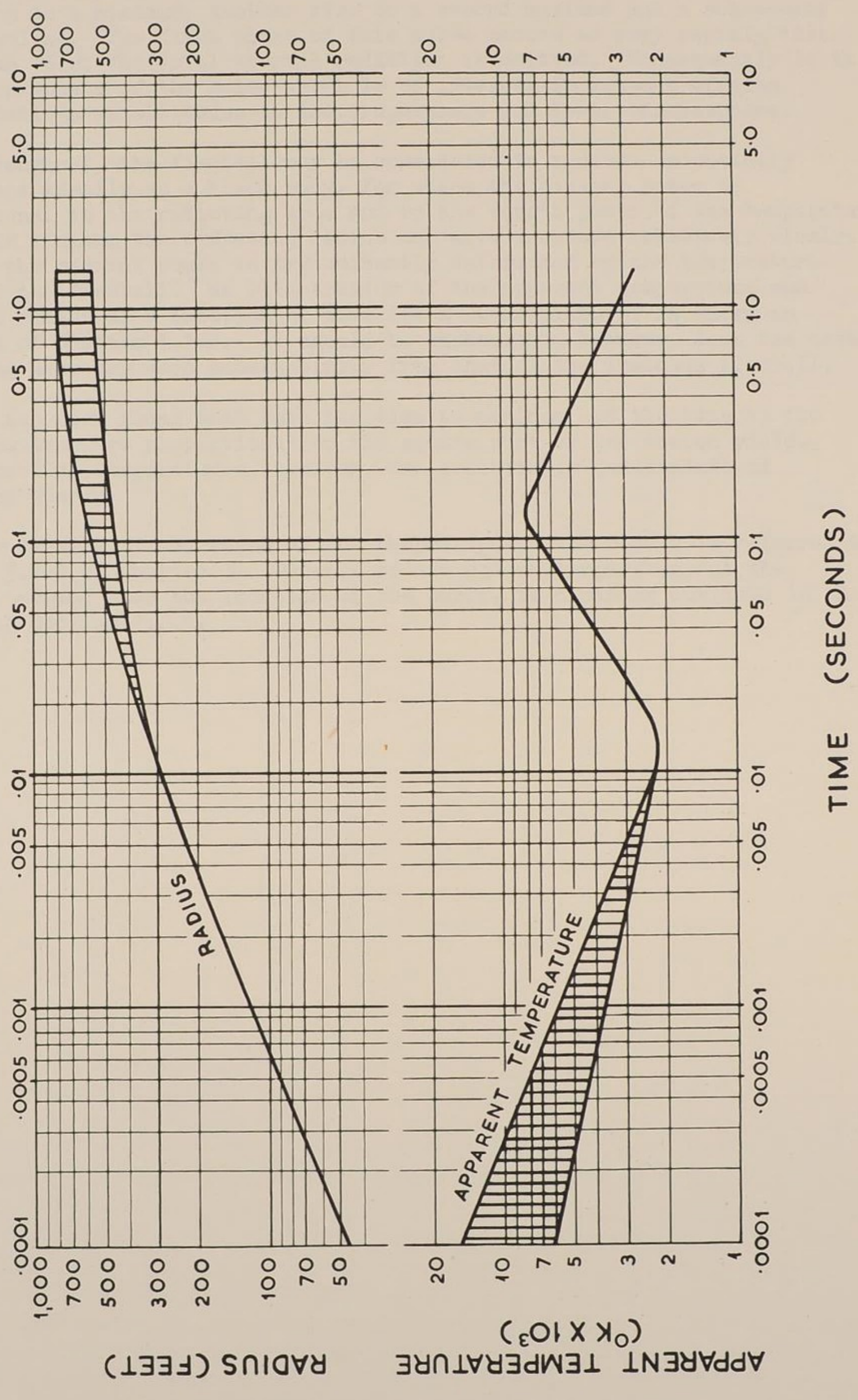
The fireball radius may be used to estimate the height of burst above which a given explosion will cause negligible local fallout. For yields less than 100 KT, the height of burst at which fallout ceases to be a significant military hazard is about 100 $W^{\frac{1}{3}}$ feet. For yields in excess of 100 KT the height of burst at which fallout is not a military hazard is not well defined, but in the absence of data the height of burst may be conservatively taken as 180 $W^{0.4}$ feet.

It must not be assumed that weapons burst above these specified heights will never present a residual radiation problem, for neutron-induced radioactivity can be very intense in a relatively small area around ground zero. (For details see Part VII, Chapter 3, Section 3.2).

Reference

(1) Effects of Nuclear Weapons U.S.A.E.C. (1957) p.66.

(2) Capabilities of Atomic Weapons. U.S. Department of the Army, Manual TM 23-200 (1957). (Confidential)



RADIUS AND APPARENT SURFACE TEMPERATURE OF FIREBALL AS A FUNCTION OF TIME (20 KT AIR BURST)

1.1.3 Temperature of the Fireball

In Section 1.1.1 the fireball was described as emitting thermal radiation in a pulse characterised by a rapid rise to a first maximum, a decline to a minimum, another rise to a second maximum and a subsequent final decline. The first phase of this pulse occurs so very rapidly that less than 1% of the total thermal radiation is emitted. Consequently it is the second phase of the pulse which is of interest in weapons effects considerations at altitudes in the troposphere and lower stratosphere.

Throughout, the fireball may be considered to radiate essentially though not ideally as a black body, for which the radiant power is proportional to the radiating area and to the fourth power of the temperature. After the minimum the radiating radius and area increase relatively slowly, so that the radiant power is predominantly determined by the temperature cycle of the fireball. An illustration of the apparent temperature and fireball radius as a function of time for a 20-KT airburst is shown in Figure 1 of Section 1.1.2. It should be emphasised, however, that the actual radiating area may vary substantially from that of the luminous fireball.

It has been found that both the time to minimum and the time to the second maximum are proportional to the square root of the weapon yield. The respective temperatures, however, are essentially independent of explosion energy.

For details of the shape of the thermal pulse the reader is referred to Section 3.2.1 of Chapter 3. Details of the colour temperature of the fireball depend upon the location of the burst, in a manner outlined in the following section 1.2.1.

1.2. Radiation from the Fireball

1.2.1. Nature of the Radiation

The thermal (or visual-thermal) radiation output from a nuclear explosion consists of an initial ultra high temperature flash (colour about 300,000°K) of very short duration, followed by the radiation from the fireball, which may vary in duration from a fraction of a second to twenty seconds, according to the size of the weapon. (For details see Section 1.1.3 and M.E.A.W. Data Sheets 3.1 and 3.3).

In very high altitude bursts, the magnitude and duration of the flash are enhanced at the expense of blast energy and radiation from the fireball (M.E.A.W. Data Sheets 3.1C and 3.3C), but apart from this special case the flash effect can generally be ignored. An exception however, is the flash effect on the human eye, which is considered in Chapter 7, Section 7.8.

The emission from the fireball is roughly "black-body" in spectral distribution, with a colour temperature of mean value about 6,000°K for an air burst, or 3,000°K for a surface burst. At wavelengths below about 0.3 micron the radiation is very heavily attenuated by the atmosphere, and the output below this value may usually be ignored. For an air burst, about 10% of the radiation will be in the transmitted ultra-violet (0.3 to 0.4 micron), and the rest will be equally divided between the visual (0.4 to 0.75 micron) and the infra-red (over 0.75 micron). For a surface burst (as viewed by a ground observer) there will be negligible ultra-violet, about 10% visible, and 90% infra-red radiation. A surface burst viewed from the air may exhibit a spectrum more nearly like an airburst.

1.2.2. Attenuation of Thermal Radiation

The thermal energy from a nuclear explosion falling upon a given area will diminish with increasing distance from the explosion for two reasons.

Firstly, the radiation will spread over an ever-increasing area as it travels away from the fireball, and will be reduced according to the inverse square law of distance.

Secondly, allowance must be made for the attenuation of the radiation by the atmosphere. The atmospheric transmittance (T) is defined as the fraction of the radiant exposure received at a given distance after passage through the atmosphere, relative to that which would have been received at the same distance if no atmosphere were present. Atmospheric transmittance depends upon several factors; among these are: water vapour and carbon dioxide absorption of infra-red radiation, ozone absorption of ultra-violet radiation, and multiple scattering of all radiation. All these factors vary with distance and the composition of the atmosphere. Scattering is produced by the reflection and refraction of light rays by certain atmospheric constituents such as dust, smoke and fog. Interactions such as scattering which divert the rays from their original paths result in a diffuse rather than direct transmission of the radiation. As a result a receiver which has a large field of view (i.e. most military targets) receives radiation which is scattered toward it from many angles as well as the directly transmitted radiation. Since the mechanisms of absorption and

scattering are wavelength dependent, the atmospheric transmittance depends not only upon the atmospheric conditions, but also upon the spectral distribution of the weapon's radiation. In Figure 1 the atmospheric transmittance is plotted as a function of the slant range for air and surface bursts. For each type of burst three sets of atmospheric conditions are assumed. It is believed that these conditions represent the average of the extremes normally encountered in natural atmospheres. These conditions correspond to a visibility of 50 miles and a water vapour concentration of 5 grammes/cubic meter; 10 miles visibility and 10 grammes/cubic meter water vapour concentration; and 2 miles visibility and 25 grammes/cubic meter of water vapour concentration. The curves of Figure 1 are plotted to slant ranges equal to half the visibility for the three visibility conditions. The reason for this is that the empirical relationships used to obtain the transmittance values have not been verified for ranges beyond half the visibility. As a result the curves cannot be extrapolated to greater distances with any confidence. If the curves are extended beyond half the visibility, there is reason to believe that the values of transmittance would be too high. Where cloud cover is appreciable or the air contains large quantities of fog or industrial haze, knowlecge of the interactions with the radiation is too limited to provide estimates of atmospheric transmittance.

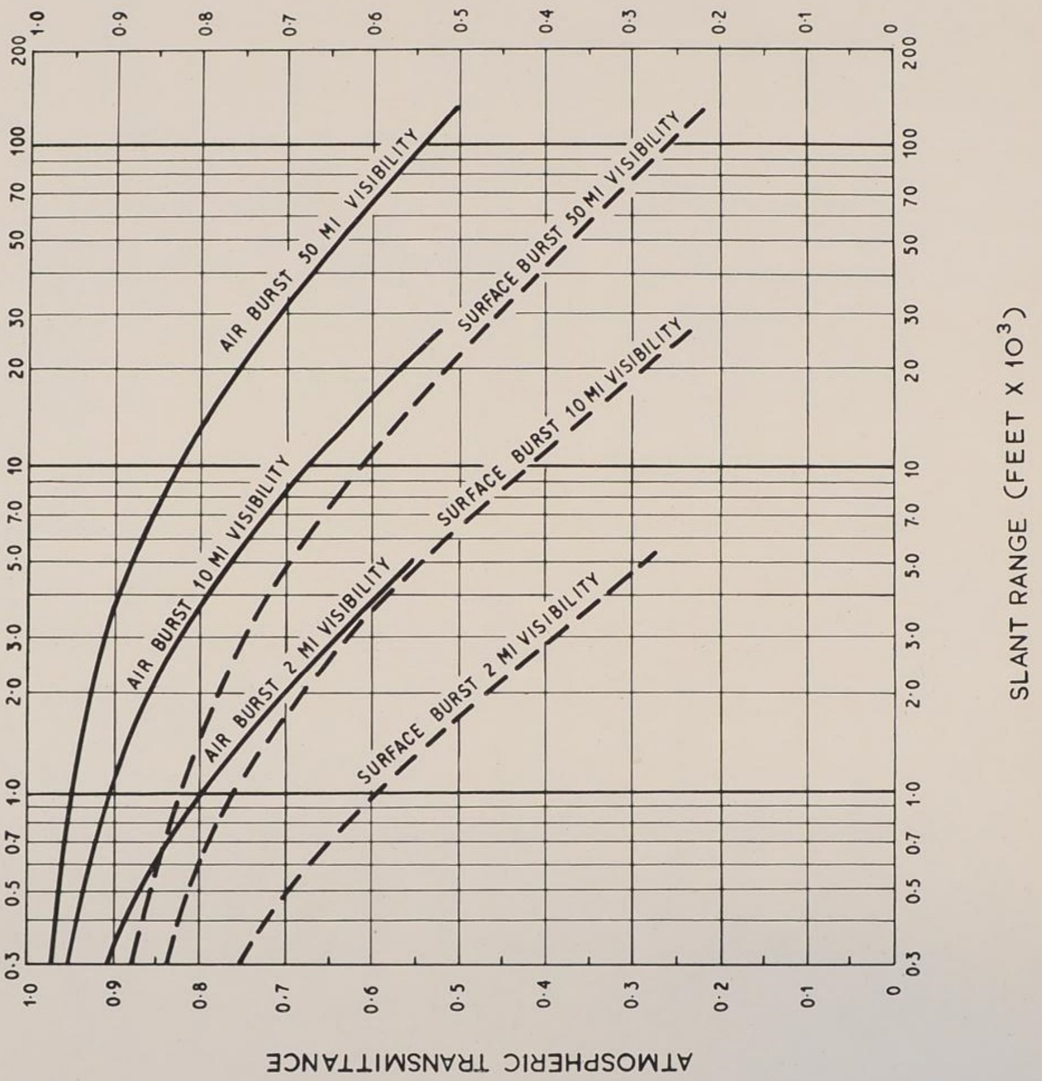
A discussion of the protection given by smoke and fog is given in section 2.4 of Chapter 2.

Some recent laboratory work is described in Reference (2).

References:

(1) Capabilities of Atomic Weapons (1957), U.S. Department of the Army. TM.23-200, page 3-2 (Confidential).

(2) Atmospheric Attenuation of Radiation. C.D.E.E. Porton Technical Paper (R)14. (Restricted).



ATMOSPHERIC TRANSMITTANCE AS A FUNCTION OF SLANT RANGE FOR AIR AND SURFACE BURSTS

1.3 Estimation of Thermal Dose

The estimation of the thermal dose received by a target falls into three stages:-

(a) Calculation of the thermal output of the explosion.

(b) Calculation of the transmission of the thermal output, i.e., the radiant exposure of the target.

(c) Calculation of the thermal energy absorbed per unit area of the target surface.

These three stages will be considered in turn.

1.3.1 Calculation of the thermal output

The effective thermal energy (E calories) of a nuclear explosion will depend upon the following factors:-

(i) the total weapon yield (W KT)

(ii) the height of burst

(iii) the height of the observer.

For airbursts under 50,000 ft.,

$$E = W/3 \text{ KT} = W/3 \times 10^{12} \text{ calories.}$$

For surface bursts viewed from the ground,

$$E = W/7 \text{ KT} = W/7 \times 10^{12} \text{ calories}$$

1.3.2 Calculation of radiant exposure

The energy Q cals/cm^2 received at a point at distance D feet from a source of thermal energy E calories is given by the equation:-

$$Q = \frac{E \cdot \bar{T}}{4\pi (30.5D)^2}$$

where $\bar{T}$ is the atmospheric transmittance.

Substituting for the values of E given in Section 1.3.1 above, we then have:-

$$Q = \frac{2.84 \times 10^7 \, W. \, \bar{T}}{D^2} \text{ cals/cm}^2 \text{ (air burst),}$$

and $$Q = \frac{1.20 \times 10^7 \, W. \, \bar{T}}{D^2} \text{ cals/cm}^2 \text{ (surface burst),}$$

where Q = radiant exposure (cals/cm^2)
$\bar{T}$ = atmospheric transmittance
W = total weapon yield (KT)
D = slant range (feet).

Curves showing the radiant exposure as a function of slant range for three atmospheric conditions, for both air and surface bursts, are given in Figure 1, taken from Reference (1). These curves are plotted for ranges up to one-half the visibility for reasons explained in Section 1.2.2 above.

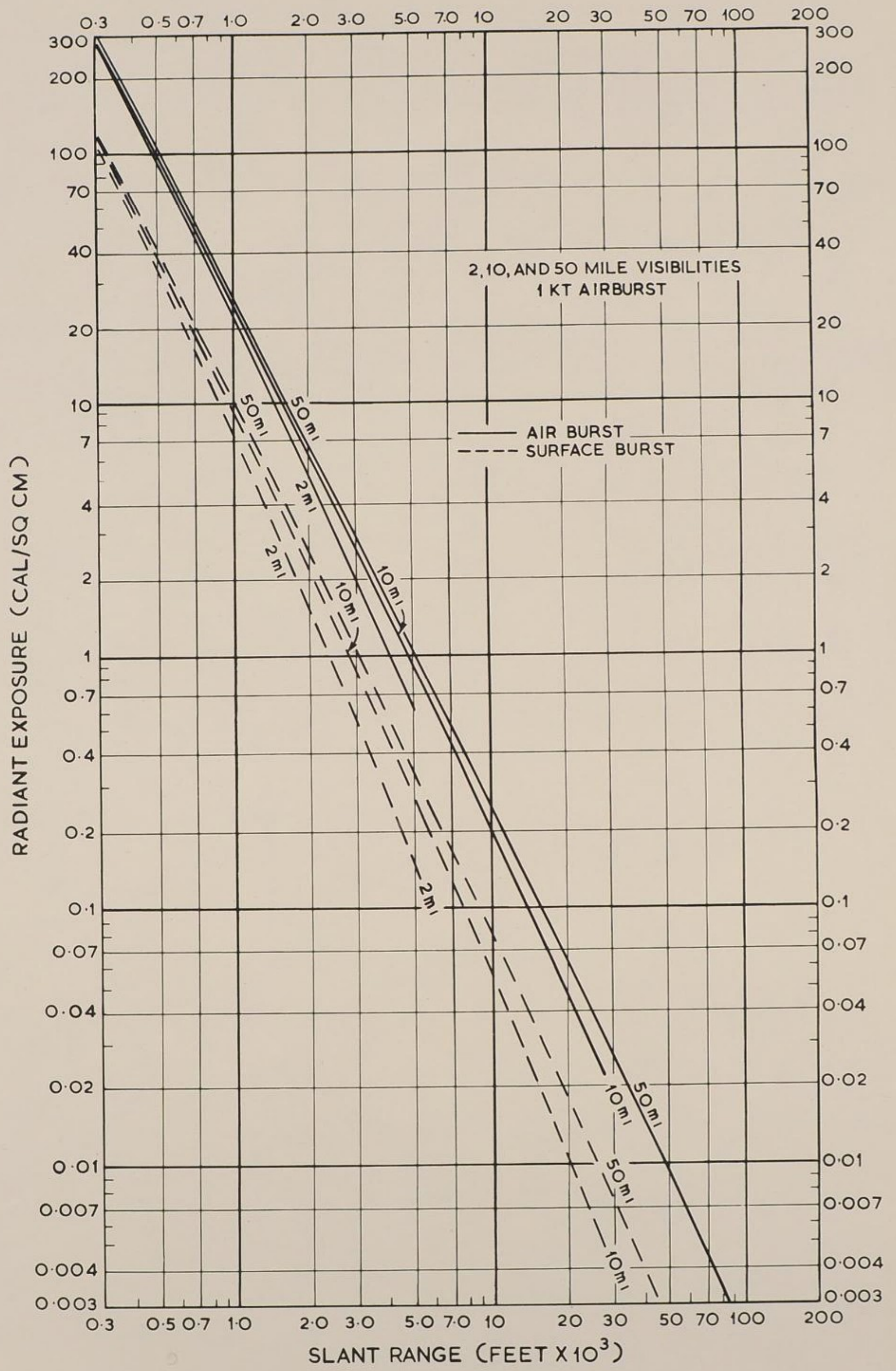
The surface burst curves differ from the air burst curves for two reasons - the apparent thermal yield when viewed from the surface for a surface burst is lower than that for an airburst, and the spectral distribution of the surface burst is sufficiently different from that of an airburst to require the use of different atmospheric transmissivity curves. Radiant exposure for a burst in the transition zone (i.e. between $180W^{0.4}$ ft. and the surface) may be estimated by linear interpolation between these curves. It should be emphasised that these surface burst curves apply to the radiant exposure of ground targets. When a surface burst is viewed from the air, as from aircraft, the area of the fireball and the thermal yield will be greater than when viewed from the ground. All the curves plotted in Figure 1 are for a total weapon yield of 1 KT. For weapon yields greater or less than 1 KT these radiant exposures should be multiplied by the yield of the weapon in question.

The effect of cloud layers above or below the burst is discussed in Reference (2).

References

(1) Capabilities of Atomic Weapons. U.S. Dept. of the Army. TM.23-200 (1957) p.3-3 (Confidential).

(2) R.A.E. Technical Memo Arm.1726. K.H. Spring, October, 1958. (Restricted).



RADIANT EXPOSURE AS A FUNCTION OF SLANT RANGE FOR AIR AND SURFACE BURSTS

1.3.3. Calculation of the energy absorbed

The thermal energy absorbed per unit area of a surface will depend upon:-

(i) The absorptivity, reflectivity and emissivity of the surface. The reflectivity (r) of a surface is equal to (1 - a), where (a) is the absorptivity, or to (100 - a) if both are expressed as percentages. The emissivity $\bar{e}$ for radiation of any particular wavelength is equal to a for the same wavelength. For a perfect black body, or a perfect grey body, a and $\bar{e}$ are equal and constant over the whole waveband. Practical surfaces are, however, selective absorbers, and there is no relation between the degree of absorption of radiation from a 6000°K source and the efficiency of emission of radiation characteristic of a temperature of 200°C to 300°C. Thus, many white surfaces, including white paints, are poor absorbers of high temperature radiation and good emitters of low temperature radiation.

(ii) The angle of incidence of the radiation. By simple geometry, if radiation of intensity Q cals/cm^2 falls onto a surface at an angle α to the normal, then the effective radiation intensity Q_α is given by:-

$$Q_\alpha = Q. \cos \alpha \text{ cals/cm}^2.$$

For most practical surfaces the absorptivity is independent of the angle of incidence, except for large angles (grazing incidence) at which the absorptivity decreases. If however, the surface has a marked structure, absorption may vary considerably as the angle of incidence increases. Such an effect may be produced by unusual surface topography, or by anisotropy in the structure of the surface. The effect must be determined for each type of surface. Uniform absorptivity should be assumed and the simple geometrical law used unless there is reason to suppose otherwise.

A further, and more detailed discussion of thermal energy absorption is given in Chapter 3, which deals with the temperature rise of irradiated materials.

CHAPTER 2 - SHADOWING AND SHIELDING

2.1. Introduction

Thermal radiation from a nuclear weapon will not be received uni-directionally, for two reasons; firstly, because of the extended size of the fireball, and secondly, because of the contribution of scattered radiation.

The effect of scattered radiation becomes significant in the estimation of doses from air burst megaton weapons at long ranges. The visible and ultra-violet part of the radiation is scattered rather than absorbed by air and will not therefore, be greatly attenuated, but will move outwards after multiple scattering. Apart from the losses by infra-red absorption, the outward flux in any element of solid angle will therefore be constant and the intensity will decay only with the inverse square law of distance. The mean free path of the photon of visible light (i.e. the average distance it travels before being scattered, or the reciprocal of the attenuation coefficient) will be of the order of 600-10,000 yards, according to visibility. At ranges of not more than one mean free-path length, the radiation will be sensibly radial, i.e. sharp shadows will be formed. At ranges of several free-path lengths the total radiation will be little attenuated except for infra-red absorption, but the outward flux will be progressively more diffuse. In any element of solid angle therefore, the radiation passing through a given cross section will be constant, but will be distributed in the form of a polar diagram. At ranges equivalent to hundreds of free-path lengths this diagram would tend to be spherical, i.e. the illumination would be nearly non-directional, but at such lengths the dose would be insignificant.

2.2. Diffuse Atmospheric Transmission. Windows.

For an accurate assessment of the amount of thermal radiation falling on a surface inclined at an angle to the source or upon a surface receiving radiation from a limited field of view (e.g. through a window) it is necessary to know the polar distribution of the radiation on arrival.

Some limited experimental work suggests that the peak intensity of the thermal radiation reaching a surface from a field of view β radians diameter directed towards the source, is given by:-

$$\overline{T}_\beta = \overline{T} + g(1 - \overline{T})(1 - e^{-\beta})$$

where $\overline{T}$ is the specular transmittance

$\overline{T}_\beta$ is the apparent transmittence for the field of view β.

$\overline{T} = e^{-\mu D}$ where μ is the mean attenuation coefficient for all wavelengths in the fireball spectrum and D is the distance of the receiving surface from the point of burst.

In the formula above $(1 - \overline{T})$ represents the amount of scattered radiation. g is a constant varying between $\frac{1}{2}$ and 1 representing the loss of scattered light to the ground. $(1 - e^{-\beta})$ is an empirical correction, determined by experiment, for the fraction of the scattered radiation coming from the field of view β. Extended experiments in the U.K. seem to suggest that doses estimated in this way will in general overestimate the diffuse dose.

A more detailed treatment of the above formula is given in M.E.A.W. Data Sheet 3.5A and M.E.A.W. Fig. 3.5.2 shows T_β as a function of $\overline{T}$ for various values of β and g.

Detailed mathematical treatments of the radiation scattering problem have been attempted in References (1) and (2).

A less sophisticated method of attack is to assume the radiation reaches the surface in three ways:-

(a) By direct specular transmission.

(b) By two rectilinear (attenuated paths) with one single scattering between them.

(c) The residual scattered radiation is then assumed to be isotropically diffuse and to reach the source uniformly from all directions.

Calculations based on this method of analysis are likely to be adequately accurate for many purposes. Some experimental and theoretical results are discussed in Reference (3).

References

(1) Sliepcevich, C.W. et alia. Attenuation of Thermal Radiation by a Dispersion of Oil Particles. Parts I and II. University of Michigan, 1954. (Unclassified).

(2) Smith, M.G. The Six Flux Method as an Approximation to the Transport Equation. A.R.D.E. Memorandum (B) 23/58. (Restricted/Discreet).

(3) Dorman, R.G. and Wootten, N.W. Atmospheric Attenuation of Radiation. C.D.E.E. Porton Technical Paper (R) 14. (Restricted).

2.3 Protection Afforded by Smokes

In the event of an air burst occurring above a layer of dense cloud, smoke or fog, an appreciable portion of the thermal radiation will be scattered upward from the top of the layer. This scattered radiation may regarded as lost as far as a point on the ground is concerned. In addition, most of the radiation which penetrates the layer will be scattered, and very little will reach the given point by direct transmission. These two effects will result in a substantial decrease in the amount of thermal energy reaching a ground target covered by fog or smoke from a nuclear explosion above the layer. Table I, taken from Reference (1) gives values for the reflectivity of various types of clouds.

TABLE I. Typical Albedo Values for Clouds

Cloud Type	Average Albedo per cent.
Very dense clouds of extensive area and great depths	78
Dense clouds, quite opaque	60
" " nearly "	44
Thin clouds	38
Strato-cumulus, overcast	70
Alto-stratus, occasional breaks	26
" " overcast	50
Cirro-stratus and alto-stratus	56
" " overcast	47
Stratus 600-1,000 ft. thick	78
Artificial smoke (concentrated)	60

Artificial (chemical) smoke acts just like a fog in attenuating thermal radiation. A dense smoke screen between the point of burst and a given target can reduce the thermal radiation energy to as little as one tenth of the amount which would otherwise be received at the target. Smoke screens would thus appear to provide the possibility of protection against thermal radiation from a nuclear explosion, if the simultaneous attenuation of sunlight is tolerable.

It is important to note that the decrease in thermal radiation by fog and smoke will be realised only if the burst point is above, or to a lesser extent within the fog (or similar layer). If the explosion should occur in moderately clear air beneath a layer of cloud or fog, some of the radiation which would normally proceed upward into space will be scattered back to earth. As a result, the thermal energy received will actually be greater than for the same atmospheric transmission conditions without fog or cloud cover.

Area smoke screens were used in World War II to protect important targets from observation, and there is considerable operational experience available from the use of these screens. However, since the opacity requirement and conditions of irradiation are different in the two cases, it is not possible at present to scale up the effect and quantities required and to give a full evaluation.

In the U.S., the use of fog oil smoke has been investigated both in the laboratory and in the field, and has been given a full-scale test in an atomic explosion. It was concluded that 200-400 gallons of fog oil per square mile of screen would reduce the thermal radiation from 10-100 KT weapons detonated at optimum height, to 3 cals/cm^2 or less at points immediately outside the 6-8 p.s.i. blast contour. Further details are given in Reference (2). A theoretical treatment of this problem is given in References (3) and (4).

Thermal attenuation by fog oil smoke is essentially by scattering alone. According to Reference (5), a material which included absorbing properties as well, such as carbon smoke, is likely to prove more economical. The weight of material in suspension could thereby be reduced, probably by a factor of a half or a third.

Reference (6) gives an account of field trials made to assess the attenuation of solar radiation by zinc hexachloroethane (HCE), which is a partial absorber owing to the presence of carbon in the smoke. From the results obtained an estimate is made of the effectiveness of HCE area smoke screens in attenuating thermal radiation from nuclear explosions.

The practical utility of smoke screens, assuming that the quantities and effort required are acceptable, turns very largely upon the frequency of occurrence of suitable weather conditions. It has been estimated that over U.S. cities meteorological conditions are favourable to the formation of smoke screens for 90-95% of the time if area sources of smoke are used, and 40-80% if line sources are employed, (Reference (2)).

References

(1) Staff Officers' Manual - Atomic Weapons Employment, U.S. Dept. of the Army, FM 101-31A p.10. (Secret Atomic)

(2) Engquist, E.H. CRLR.466. "Interim Comprehensive Report on Thermal Radiation Attenuation by Oil - Fog Smoke Screens". U.S. Chemical Corps. 23.3.55.

(3) Chu, C.M., and Churchill, S.W. J.Phys.Chem., 1955, Vol. 59, p.855.

(4) Sliepcevich, C.W. "Attenuation of Thermal Radiation by a Dispersion of Oil Particles", Parts I and II. University of Michigan, 1954.

(5) Ford, J.J. CRLR.252. "Thermal Attenuation Effects of Black Smoke". U.S. Chemical Corps, 10.9.53.

(6) Sawyer, K.F., and Wootten, N.W. "Field Trials on the Attenuation of Solar Radiation by Smoke Screens". Porton Technical Paper (R)1. August, 1956. (Confidential/Discreet)

2.4. Effectiveness of Shielding

Apart from the effects of scattering the thermal radiation from a nuclear explosion travels in straight lines from the fireball. Any solid opaque material such as a wall, a hill, or a tree between a given target and the fireball may act as a shield and provide protection from thermal radiation. Instances of such shielding observed after a nuclear explosion in Japan are given in Reference (1).

A shield which merely intervenes between a given target and the ball of fire, but does not surround the target, may not be entirely effective under hazy atmospheric conditions. A large proportion of the thermal radiation received, especially at considerable distances from the explosion, has undergone scattering (see Sections 2.1, 2.2, and 2.3) and will arrive from all directions, not merely that from the point of burst. It should also be borne in mind that at close ranges, where the fireball subtends a relatively large angle, the shadowing effects of intervening objects are less than are experienced with the sun.

An assessment of the value to troops of slit trenches, as protection against thermal and gamma radiations from nuclear explosions, is given in Reference (2). It is concluded that open slit trenches afford considerable overall protection to personnel against thermal and gamma effects of nuclear weapons. Even when least effective (i.e. against high air bursts), they may be expected to save about 40% of the total casualties (from nuclear and thermal radiation) which would result from all men being in the open. This figure increases with decreasing burst height, up to a maximum of about 97% for low air bursts. Trenches with thermal screens afford much greater protection than open trenches against high air bursts, but about the same protection against low air bursts.

In a report on the vulnerability of Armoured Fighting Vehicles and their crews to nuclear weapons (Reference (3)), an assessment is made of the protection afforded against thermal radiation. It is concluded that closed-down vehicles give good protection against thermal radiation, but that there is a possibility of burns being caused by the transmission of radiation through optical instruments.

Transparent materials such as glass and plastics allow thermal radiation to pass through only slightly attenuated. Methods of treating window-glass to provide heat radiation shields are described in Reference (4). These methods consist in applying a coating to the window which reduces the radiation transmitted and scatters the part which is transmitted. Thus not only is the total quantity of heat entering the room reduced, but its intensity is more evenly distributed. The best coatings for this purpose are white, and those that last longest are of the high gloss or cement paint type; emulsion paints are ineffective. The protection is reduced if the windows are blown out by the blast wave before all the thermal energy is delivered.

References

(1) Effects of Nuclear Weapons. U.S.A.E.C., 1957, pages 312-316.

(2) A.O.R.G. Report No. 12/55 "The Protective Value to Personnel of Slit Trenches against Thermal and Gamma Radiation Effects of Nuclear Explosions. (Secret/U.K. Eyes Only)

(3) A.O.R.G. Report No. 4/58 - "The Vulnerability of Armoured Fighting Vehicles and Their Crews to Nuclear Weapons". (Secret/Discreet)

(4) Joint Fire Research Organisation S.R. Note 28/1956 "Heat Radiation Shields for Defence against Atomic Explosions". Simms D.L., Hinkley, P.L., and Weston, M.A. (Confidential).

CHAPTER 3 - THE TEMPERATURE RISE OF IRRADIATED MATERIALS

3.1. Introduction

There are many important physical properties which determine the temperature rise of irradiated materials. Among these are:-

(a) the intensity of the incident radiation; (I cal/cm^2/sec).

(b) the duration of the irradiation; (t secs).

(c) the reflectivity or absorptivity of the material; (r) or (a).

(d) the transmittance of the material; ($\overline{t}$).

(e) the thermal properties of the material, i.e.

thermal conductivity	(K cal/cm/sec/$^\circ$C)
specific heat	(c cal/gm/$^\circ$C)
density	(ρ gm/cc)

(f) the thickness of the material; (2 ℓ cm).

(g) the heat transfer coefficient for cooling losses from the surface by convection and re-radiation. (H cal/cm^2/sec/$^\circ$C). (The Newtonian Cooling Constant).

(h) the chemical heating if the material is not inert.

In calculating the temperature rise of an irradiated solid it is necessary to make certain simplifying assumptions. These assumptions cannot be made without loss of accuracy, but when thermal damage from nuclear explosions is estimated, only approximate information is available on such matters as the effect of the atmosphere on the transmission of raidation and the actual thermal yield of the bomb. Useful quantitative results can be obtained since prediction errors are likely to be relatively small compared with various other practical uncertainties.

3.2. Factors Influencing the Temperature Rise

3.2.1. Irradiation Intensity

The shape of the thermal pulse after the radiant power minimum is sufficiently similar for nuclear detonations that a single curve may represent the time distribution of radiant power emitted (Figure 1). This curve has been developed by using ratios. The ratio $^{p}/p$ max is plotted against the ratio $^{t}/t$ max, where $^{p}/p$ max is the ratio of the radiant power at a given time to the maximum radiant power, and $^{t}/t$ max is the ratio of time after detonation to the time of the second thermal maximum after that detonation.

The percentage of the total thermal radiation emitted as a function of the ratio $^{t}/t$ max is also shown on Figure 1. From this figure it is seen that approximately 20% of the total emission occurs up to the time of the second power maximum, whereas approximately 80% is emitted prior to 10 times the time to the second maximum. By this time the rate of delivery has dropped to such a low value that the remaining energy is no longer of significance in damage production, although the fireball still appears brilliant to the eye until approximately 50^{t} max.

It has been found that both the time to the minimum and the time to the second maximum are proportional to the square root of the weapon yield. Thus for airbursts at altitudes of burst below about 50,000 ft., the time to minimum is $0.0027W^{\frac{1}{2}}$ seconds. The time to the second maximum is $0.032W^{\frac{1}{2}}$ seconds. (See Figure 2: these curves may also be used for surface bursts.) It should be noted that for weapon yields lower than approximately 6 KT the actual values of t max may be as much as 30% higher than those given by Figure 2. This is caused by the higher mass-to-yield ratio characteristic of low yield weapons. These relations indicate that a 1 megaton weapon delivers its thermal radiation over a period 32 times as great as does a 1 KT weapon. Hence it is to be expected that the thermal energy required to produce a given degree of damage will increase with the energy yield of the explosion, e.g. see Table 2 of Section 4.2.1 Chapter 4 - Critical Radiant Exposure Values for various Fabrics.

References

(1) Capabilities of Atomic Weapons (1957) - U.S. Dept. of the Army, TM 23-200, p. 3-1. (Confidential).

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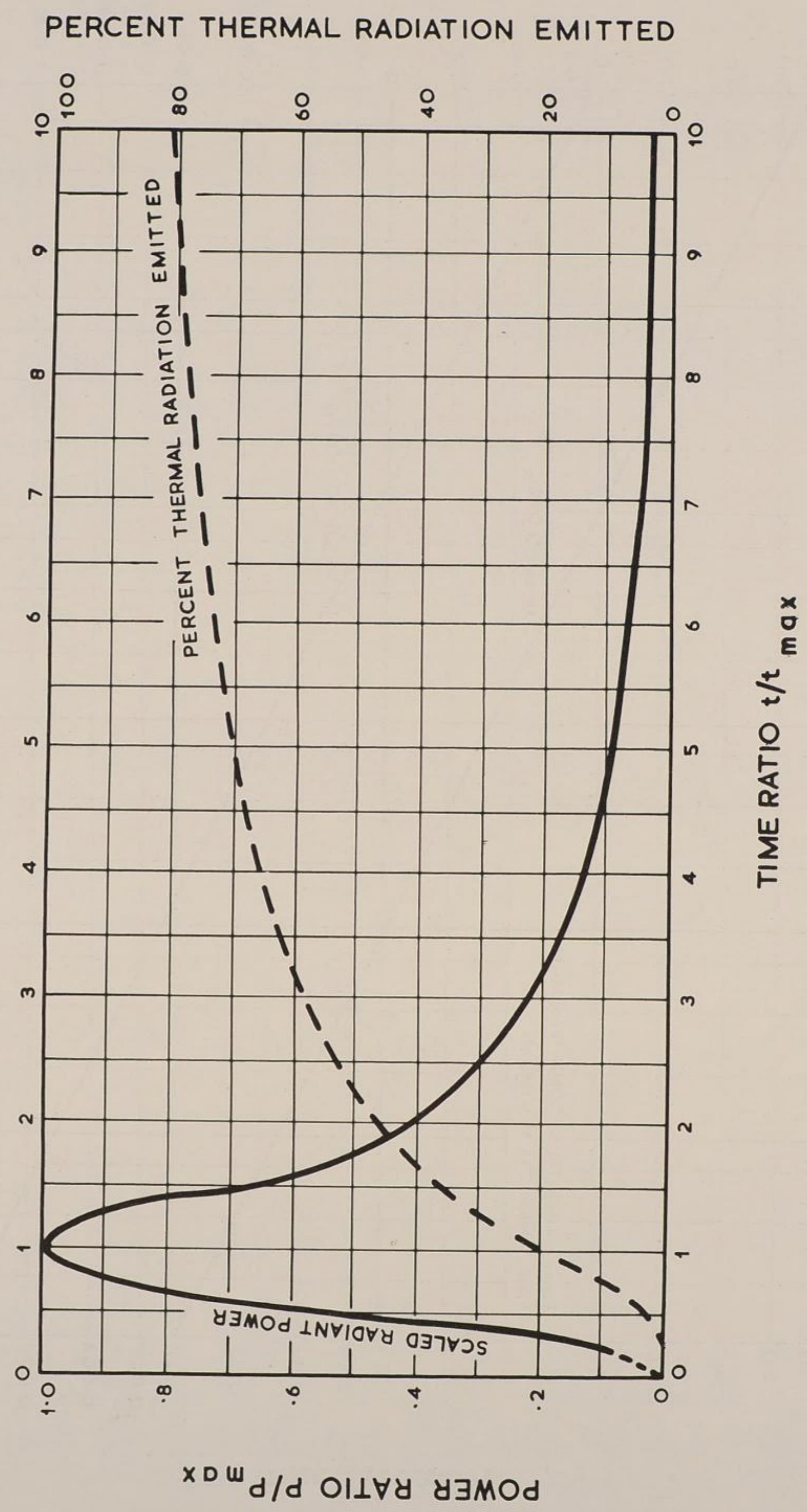

GENERALISED THERMAL PULSE

PART VI
CHAPTER 3
SECTION 3.2.1
FIGURE 2

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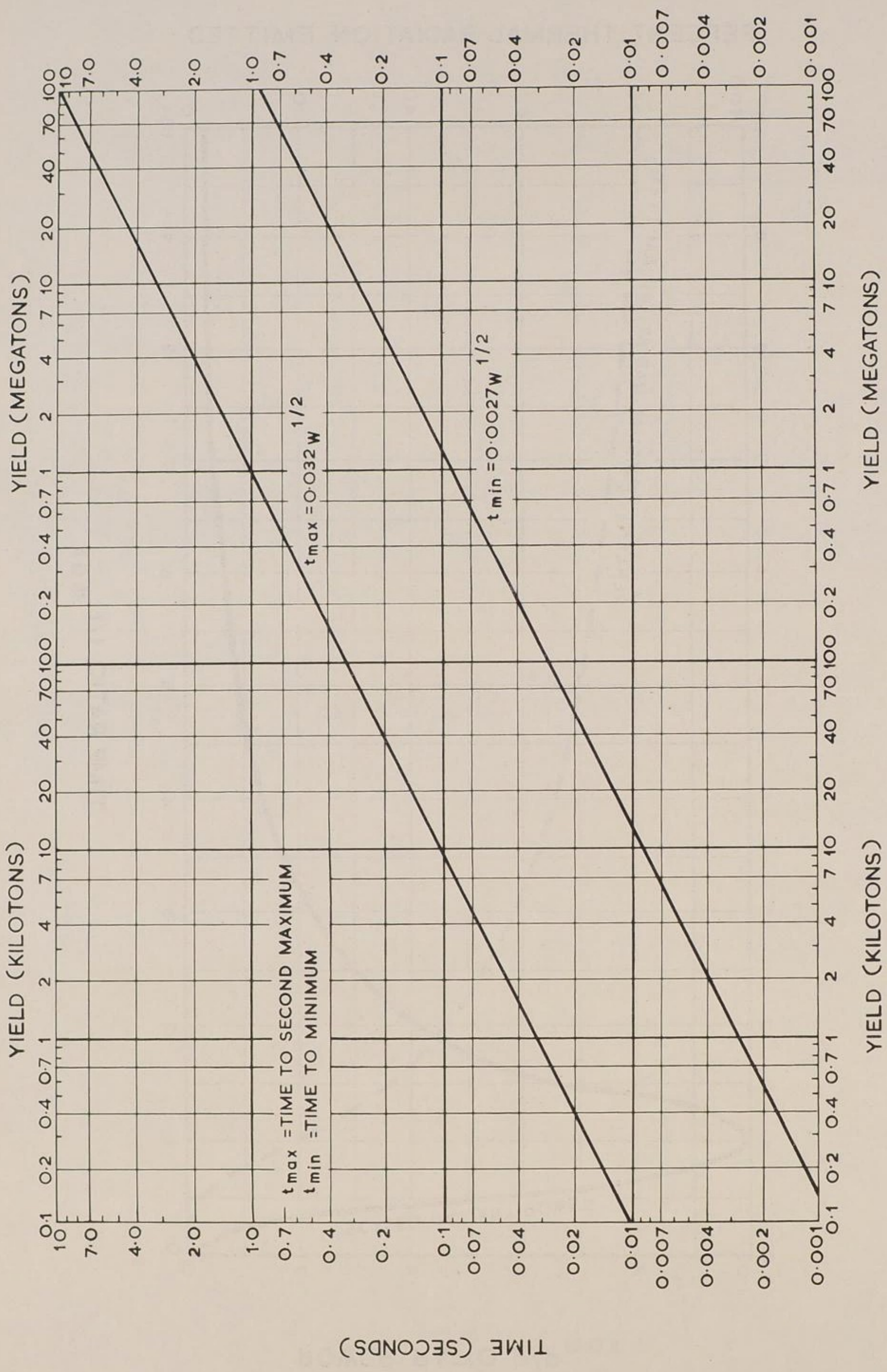

PULSE TIMING AS A FUNCTION OF WEAPON YIELD

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3.2.2. Physical properties of the material

(a) Absorption of radiation

Radiation incident upon a surface may be partly absorbed, partly reflected and partly transmitted. It is the absorbed heat which produces the temperature rise in materials, which then re-radiate according to their emissivity.

If radiation strikes the surface normally the fraction (I) absorbed is given by -

$$I = aI_o$$

i.e. $$I = I_o(1 - r - \overline{t}) \qquad (1)$$

where I_o is the incident radiation

a is the absorptivity

r is the mean reflectance,

and $\overline{t}$ is the transmittance, for a given range of wavelengths and surface conditions.

The variation of I with the angle of incidence of the radiation may be calculated from a simple geometrical law (see Section 1.3.3. Chapter 1), which states that the amount of radiation absorbed by unit area of a surface is proportional to the cosine of the angle of incidence. This law is only approximate in practice; calculations using it give slight under-estimates of damage by a given thermal dose.

If absorption cannot be regarded as wholly occurring at the surface (e.g. in the case of glass and plastics) then the Bougier-Lambert Law may sometimes apply. This states:-

$$I(x) = (1 - r)\ I\ (0) - \gamma . e^{-\gamma x} \qquad (2)$$

where x is the distance along the radiation path;

I(x) and I(0) are the radiant intensities at a depth x and at the surface respectively, and γ is the extinction coefficient.

γ varies with wavelength, so that the transmitted radiation may not have the same composition as the incident radiation.

As a first approximation, the temperature rise of a material is proportional to the absorbed radiation. Differences in absorptivity of the surface, particularly when "a" is small, as in the case of reflecting and transmitting materials, can be an important factor in determining thermal damage.

The absorptivity of a surface may vary considerably with wavelength, as may be seen from the example given in Figure 1. A mean value may be obtained and used for radiation characteristic of a given temperature, but a different mean value may have to be used for radiation from sources at different temperatures. This means that care must be taken in using published information, because the mean absorptivity for low temperature re-radiation is not necessarily equal to the average absorptivity for high temperature irradiation. Some values for typical materials are given in Table 1 below.

TABLE 1

Percentage absorption of different materials for different wavelengths of thermal radiation

Material	Source of Temperature			
	Ignition point	Average fire	Surface burst AW	Air burst AW
	800°K	1,100°K	3,000°K	6,000°K
	Per Cent	Per Cent	Per Cent	Per Cent
Gaberdine (Forestry Green)	-	70	65	75
Cotton Twill (White)	-	45	35	30
Cotton Twill (Grey)	60	-	65	80
Cotton Sateen (Dark)	-	40	55	75
Serge (Dark Blue)	-	65	70	85
Fibre Insulating Board	71	-	35	40
Oak	-	70	45	60
Mahogany	74	-	40	55
Steel (polished)	10	20	40	45
" (oxidised)	80	-	-	-
Copper	5	13	25	-
Aluminium (polished)	8	18	35	45
" (oxidised)	75	-	-	-

This means that whilst the colour of a material may be a guide to its reflectivity to the visible portion in the spectrum, it may not be relevant to the reflectivity in the infra-red. In addition, if the absorptivity of the surface varies with its temperature, as for example the charring of wood, discoloration of paints, surface oxidation of metal, then substantial errors may be made in estimating the temperature rise. This is particularly true for materials which have a low absorptivity, where the effects of only a slight deterioration in the surface quality can be important.

Empirical correction factors have been obtained for cellulosic materials (Reference (1)) where the changes occur gradually. These are given in Table 2. For shorter exposure times the effective absorption is less. In the absence of any other information the mean value of the initial and final absorptivities should be used.

TABLE 2

Correction Factors for Absorption
by Cellulosic Materials

Material	For time of irradiation greater than (seconds)	Effective Absorption factor for Radiation of 6000°K
African mahogany	10	0.95
Western Red Cedar	7	0.7
European Oak	10	0.7
White Cotton	3	0.3

Further data on absorptivities of metal and painted metal surfaces are given in Sections 4.3.1 and 4.3.2 respectively, of Chapter 4.

(b) Transmittance

The great majority of materials may be considered opaque to radiation. The exceptions are glass, and perspex and similar plastics, although many fabrics - especially those of loose weave and light weight - transmit some of the radiation directly, as given in Reference (8).

Few figures are available for the value of γ, the extinction coefficient, for most non-combustibles except glass (Reference (2)). Some figures which are not generally available, for plastics for wavelengths in the range 500-950 microns are given in Table 3 (from Reference (3)).

TABLE 3

Some Extinction Coefficients
of Plastic Materials

Plastic	Wavelength 500-950 microns Extinction Coefficient (cm^{-1})
Methyl methacrylate (Perspex)	0.66
Allyl alcohol	0.32
Cellulose acetate butyrate	2.4
Cellulose acetate	1.9
Cellulose nitrate	1.3
Cellulose propionate	4.3
Ethyl cellulose	1.6
Polystyrene	2.4

Some materials normally thought of as opaque, for example wood, are influenced in their normal behaviour by transmittance, particularly where the exposure is short (Reference (4)). The fact that radiation is not all absorbed at the surface may mean that the temperature in the immediate interior is slightly higher than for an opaque material, whilst the surface temperature will be slightly lower.

(c) Thermal conductivity

The thermal conductivity of all materials varies with the temperature; for most pure metals it might be expected to be inversely proportional to the absolute temperature. Little information on this is available for non-metals, but the values may change if a vigorous chemical reaction should occur. If moisture is present, the thermal conductivity of wood or insulating materials may be increased significantly (Reference (5)). The presence of an air gap in the material will decrease its conductivity considerably. For short exposures, such as are being considered here, air gaps may prevent heat penetratimg to the interior altogether. This is often of great importance in preventing burns to the skin through clothing.

(d) Density

This may usually be taken as constant.

(e) Specific heat

This may vary with temperature. If the material holds moisture the apparent specific heat may increase considerably (Reference (6)). See also Section 3.2.4 of this chapter.

Table 4 gives values of the thermal constants for a wide range of materials (Reference (7)).

Reference

(1) Simms, D.L., Law, Margaret and Hinkley, P.L. The Effect of Absorptivity on the Ignition of Materials by Radiation. J.F.R.O. F.R. Note No. 308/1957.

(2) Smithsonian Physical Tables, Washington, 1954, page 512.

(3) Lawrence, E.K. Analytical Study of Flame Initiation (M.Sc. Thesis) Department of Chemical Engineering, Massachusetts Institute of Technology, U.S.A. (1952).

(4) Gardon, R. Thermal Damage Initiation in Organic Materials Technical Report No. 2. Fuel Research Laboratory, Massachusetts Institute of Technology, U.S.A.

(5) Maclean, J.D. "Thermal Conductivity of Wood". Heating, Piping and Air Conditioning, 1941, Vol. 13, pages 380-391.

(6) Hearman, R.F.S. and Burchan, J.N. "Specific Heat and Heat of Wetting of Wood". Nature, November 26, 1955, page 978.

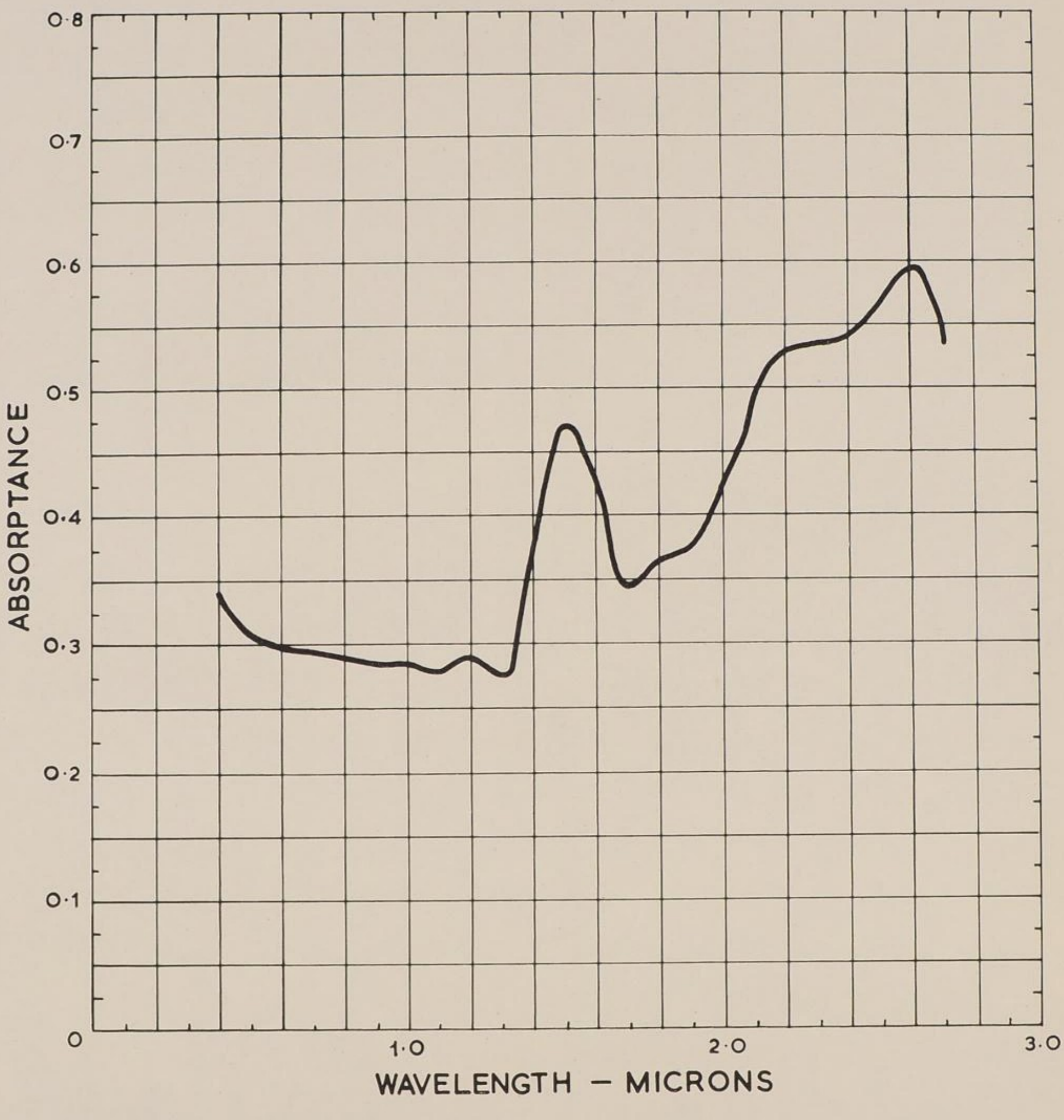
(7) Wilkes, G.B. "Heat Insulation". John Wiley, 1950.

(8) Richards, H.R., and Fuoco R., "An evaluation of some cotton textile fabrics". Defence Research Chemical Laboratories, Report No. 278, Ottawa, April 1958.

TABLE 4

Thermal Constants for Various Materials

Material	Density ρ	Specific heat c	Conductivity K	Diffusivity k
	gm/cm^3	cal/gm	cal/cm/sec/°C	cm^2/sec
WOODS				
Western red cedar	0.36	0.34	21×10^{-5}	1.73×10^{-3}
American white wood	0.47	0.34	29×10^{-5}	2.0×10^{-3}
African mahogany	0.56	0.34	33×10^{-5}	2.0×10^{-3}
Freijo	0.58	0.34	33×10^{-5}	2.0×10^{-3}
Oak	0.61	0.34	35×10^{-5}	2.0×10^{-3}
Iroko	0.72	0.34	41×10^{-5}	2.0×10^{-3}
METALS				
Copper	8.9	0.09	0.93	1.14
Silver	10.5	0.56	1.00	0.171
Gold	9.30	0.03	0.93	1.18
Magnesium	1.7	0.24	0.38	0.91
Aluminium	2.7	0.21	0.48	0.86
Zinc	7.1	0.92	0.27	0.111
Tin	7.3	0.53	0.15	0.038
Brass 70 : 30	8.5	0.09	0.25	0.33
Platinum	21.5	0.03	0.17	0.25
Lead	11.3	0.03	0.08	0.25
(0.1%C) mild steel	7.9	0.12	0.11	0.12
Cast iron	7.4	0.14	0.12	0.12
Bismuth	9.8	0.03	0.02	0.07
Mercury	13.6	0.03	0.02	0.04
BUILDING MATERIALS				
Fibre insulating board	0.24	0.34	8.5×10^{-5}	1.04×10^{-3}
Brick	1.44-2.24	0.20-0.22	$13\text{-}32 \times 10^{-4}$	$44\text{-}67 \times 10^{-4}$
Concrete (gravel)	2.16-2.29	0.22-0.23	$57\text{-}33 \times 10^{-4}$	$65\text{-}120 \times 10^{-4}$
Foamed slag concrete	1.04	0.23	5.7×10^{-4}	24×10^{-4}
Cellular concrete	0.64	0.25	3.4×10^{-4}	21×10^{-4}
Glass	2.11-2.6	0.16	2.1×10^{-3}	5.2×10^{-3}
Slag wool	0.19-0.30	0.18	$0.9\text{-}1.4 \times 10^{-4}$	$26\text{-}27 \times 10^{-4}$
BOARDS OR BLOCKS				
Asbestos paper				
Corrugated	0.25	0.24	1.46×10^{-4}	24.2×10^{-4}
Laminated	0.35	0.24	1.5×10^{-4}	18×10^{-4}
Corkboard	0.13	0.42	1.0×10^{-4}	18×10^{-4}
Fibre glass	0.032	0.13	8.5×10^{-5}	1.9×10^{-2}
POWDERS				
Charcoal	0.18	0.25	1.2×10^{-4}	26.8×10^{-4}
Ground cork	0.15	0.48	1×10^{-4}	0.0014
Soil (Average)	2.5	0.2	23×10^{-4}	0.0046
Soil (Sandy dry)	1.65	0.19	6.3×10^{-4}	0.0020
Soil (Sandy moist 8%)	1.75	0.24	14×10^{-4}	0.0033



VARIATION OF ABSORPTANCE WITH WAVELENGTH
FOR A WHITE COTTON TWILL

3.2.3. Homogeneity of the material

The most important types of non-homogeneous materials are thin films on a combustible base material, and clothing on the body. A thin film on the surface of the material may have two effects (Reference (1)).

(a) If it is opaque it may change the emissivity and absorptivity of the material underneath. In estimating the temperature rise, the emissivity of the film should be taken, provided that the film is not rapidly destroyed by the heat.

(b) It may, if applied sufficiently thickly, remove the capacity of transparent material to transmit radiant heat.

Either effect may alter the rise in temperature of the surface. In general, thin films of good conductors have little effect on bad conductors, whilst a thin film of a bad conductor may have a marked effect on both good and bad conductors. (Reference (2)). The most effective barrier is one of a high thermal capacity and low conductivity, (Reference (3)). It is important to realise that changing the base material will change the temperature rise in both materials.

References

(1) Leedy, R.N. "Control of Radiant Heat by Surface Finish". Westinghouse Engineer, 1954, Vol. 14, pages 147-157.

(2) Carslaw, H.S. and Jaeger, J. C. "Conduction of Heat in Solids". Oxford, 1948, Clarendon Press, pages 54-55.

(3) Pickard, R. W. "The Thermal Insulation Afforded by a Fire Retardant Coating". Joint Fire Research Organisation, F.R. Note 155/55.

3.2.4. The effects of moisture and chemical reactions

(a) Moisture content

Materials come to equilibrium with the moisture in the atmosphere. The amount they contain is normally expressed as a percentage by weight and is usually not considerable except for organic materials. The presence of water may affect the temperature rise in three ways. It will increase the thermal properties (capacity, density, conductivity); it will absorb latent heat in evaporation; and water vapour will diffuse from the hot to the cold portions, (Reference (1)). The resultant effect is often difficult to estimate. In general, the temperature rise of the front surface is reduced, whilst the temperature rise of the rear surface of loosely woven materials may actually increase, leading to burns (Reference (2)).

There is some controversy about the effect of moisture in such materials as concrete, bricks and asbestos cement; for instance, it has been suggested that water vapour might be the cause of spalling.

(b) Chemical reactions

Depending upon the type of material, various reactions may occur. At the high temperatures that may be attained, paints carbonise, wood blackens, common metals oxidise. These effects may change the thermal properties and the absorptivity. In addition, they may lead to the generation of heat.

/For

For organic materials such as wood, this is probably negligible below 500°C (References (3) and (4)). Estimates of damage suffered neglecting chemical heating will be conservative. Endothermic reactions having the reverse effect, can confer some protection.

References

(1) Solvarson, K. R. "Moisture in Transient Heat Flow". Heating, Piping and Air Conditioning, 1955, Vol. 27, pages 137-142.

(2) Simms, D. L., Hinkley, P. L., and Roberts, Valerie E. "The effect of water in clothing". Joint Fire Research Organisation S.R. Note No. 366/1958.

(3) Thomas, P. H. and Simms, D. L. "Thermal Damage Initiation by Radiation and Chemical Decomposition - Some Theoretical Aspects". Joint Fire Research Organization, F.R. Note No. 331/1957.

(4) Lawrence, E. K. "Analytical Study of Flame Initiation". M.Sc. Thesis, Department of Chemical Engineering, Massachusetts Institute of Technology, 1952.

3.2.5. Heat losses

(a) Heat loss from surface

Any hot body loses heat from its surface by radiation and convection. An expression for the heat loss (q) from the surface is -

$$q = \bar{e}\sigma(T^4 - T_o^4) + H'(T - T_o) \qquad (1)$$

where $\bar{e}\sigma(T^4 - T_o^4)$ represents the radiation loss according to the Stefan-Boltzmann law, with $\bar{e}$ the mean emissivity from the surface over the temperature range from T_o to T, and σ the Stefan-Boltzmann constant.

The convection loss is represented by the term $H'(T - T_o)$ where H' is the convective heat transfer coefficient.

For most calculations, it is sufficient to use the so-called Newtonian Cooling Law and choose the best value of H, the Newtonian cooling constant, for the temperature range used (Reference (1)), ie.

$$q = H(T - T_o) \qquad (2)$$

Heat losses by re-radiation and convective cooling may be neglected for small bombs (up to 20 KT), have only a marginal effect for medium size bombs (20-50 KT), but must be considered for bombs greater than 50 KT. This may be seen from Figures 2 and 3, and Figures 6 and 7, of Section 3.3.

(b) Heat loss to the interior

For short irradiation times, most materials may be considered to be semi-infinite solids. For thin materials, especially those that are good conductors, there may be some heat losses from the back surface. The effect is further considered in Section 3.3.

Reference

(1) Lawson, D. I., Fox, L. L. and Webster, C. T. "The Heating of Panels by Flue Pipes". Fire Research Special Report No. 1. H.M. Stationery Office, London, 1950.

3.3. Calculation of the temperature rise of an irradiated slab

It is assumed that:-

(a) the absorptivity of the surface is constant;

(b) the energy is absorbed at the surface;

(c) the material is dry and inert;

(d) the material is homogeneous.

The temperature rise θ, of a solid bounded by two parallel planes (a slab) of thickness 2l, losing heat from both faces by Newtonian cooling, and exposed on one face of absorptivity a to a constant intensity of radiation I, is obtained from:-

$$\frac{\partial^2\theta}{\partial x^2} = \frac{1}{k}\frac{\partial\theta}{\partial t} \qquad (t > 0) \qquad (1)$$

$$\frac{aI}{K} = h\theta + \frac{\partial\theta}{\partial x} \qquad (x = +l) \qquad (2)$$

$$h\theta = -\frac{\partial\theta}{\partial x} \qquad (x = -l) \qquad (3)$$

$$\theta = 0 \qquad (t = 0) \qquad (4)$$

where $h = \frac{H}{K}$

H is the Newtonian cooling constant

k is the thermal diffusivity $= K/\rho c$

K is the thermal conductivity

ρ is the density

c is the specific heat of the irradiated material

t is the irradiation time

x is the distance within the solid

The solution to these equations is complex (References (1) and (2)). However, within certain ranges of values of two dimensionless groups, the Fourier number kt/l^2, and the Biot number hl, useful approximations may be made. These are shown diagrammatically in Figure 1.

(i) The uniform slab

For the region A, in Figure 1, there are in effect no temperature gradiants within the solid. The mean temperature rise θ_M and the surface temperature rise θ_F are given by:-

$$\theta_F = \theta_M = I/2H \left(1 - e^{\frac{-Ht}{\rho cl}}\right) \qquad (5)$$

This is plotted in dimensionless form in Figure 2.

(ii) The non-uniform slab

For the regions A, B, C, D in Figure 1 there is a linear temperature gradient through the slab and the mean temperature is given by equation (5). The difference between the front surface temperature θ_F, and the mean temperature θ_M is given by:-

$$\theta_F - \theta_M = \frac{Ihl}{2H(1 + hl)} \tag{6}$$

Regions where $\frac{\theta_F - \theta_M}{\theta_M}$ is less than 25 and 50 per cent respectively are shown as B and C in Figure 1.

(iii) The transient case with a finite slab

No simple solution exists for this case. It is probably easiest to estimate the temperature rise by interpolation between case (ii) and case (iv).

(iv) The semi-infinite solid

For the region E in Figure 1 there is an insignificant rise in temperature of the rear surface and the temperature rise of the front surface is given by:-

$$\theta_F = \frac{I}{H} \left(1 - e^{\beta^2} . \operatorname{erfc}\beta\right) \tag{7}$$

where $\beta = \frac{H}{K}\sqrt{kt} = h\sqrt{kt}$

Equation (7) is shown plotted in dimensionless form in Figure 3.

The temperature rise within the solid is given by equation (8).

$$\theta = \frac{I}{H} \left[\operatorname{erfc}\frac{x}{2\sqrt{kt}} - e^{(hx + h^2kt)} \operatorname{erfc}\left(\frac{x}{2\sqrt{kt}} + h\sqrt{kt}\right) \right] \tag{8}$$

Solutions of equation (8) are given in Figure 5.

In order to estimate the temperature rise, it is necessary to obtain a value for the dimensionless groups, β or $\frac{Ht}{\rho cl}$ and hl. The thermal constants may be obtained from Table 4. (Section 3.2.2.) A value for H may be estimated from Figure 4, and the rise in temperature may then be read from Figure 2 or 3. If this temperature rise does not agree with the value used for choosing H, a more accurate value for H may be chosen to obtain a closer approximation to the temperature rise.

Varying impulses of radiation

The scaling laws obeyed by the pulse of radiation (given in Section 3.2.1) make the computation of temperature rise fairly straightforward for all sizes of explosion.

The surface temperature rise of a semi-infinite solid may be computed by an electrical analogue (Reference (3)) and is shown in Figure 6. An analytical solution for the mean temperature of a slab with a linear temperature gradient has been obtained (Reference (4)) and is shown in Figure 7.

References

(1) Simms, D.. L. "The Correlation of Ignition Time with the Physical Properties of Materials, Part I. Spontaneous Ignition of Cellulosic Materials". Joint Fire Research Organization, F.R. Note No. 319/1957.

(2) Carslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids (O.U.P.).

(3) Lawson, D. I. and McGuire, J. H. "The Representation of Distributed Resistance and Shunt Capacitance Circuits by Lumped Networks". Joint Fire Research Organization, F.R. Note No. 196/1955.

(4) Thomas, P. H., Simms, D. L., and Law, Margaret. "The correlation of the threshold for ignition by radiation with the physical properties of materials". Joint Fire Research Organisation, F.R. Note No. 381/1958.

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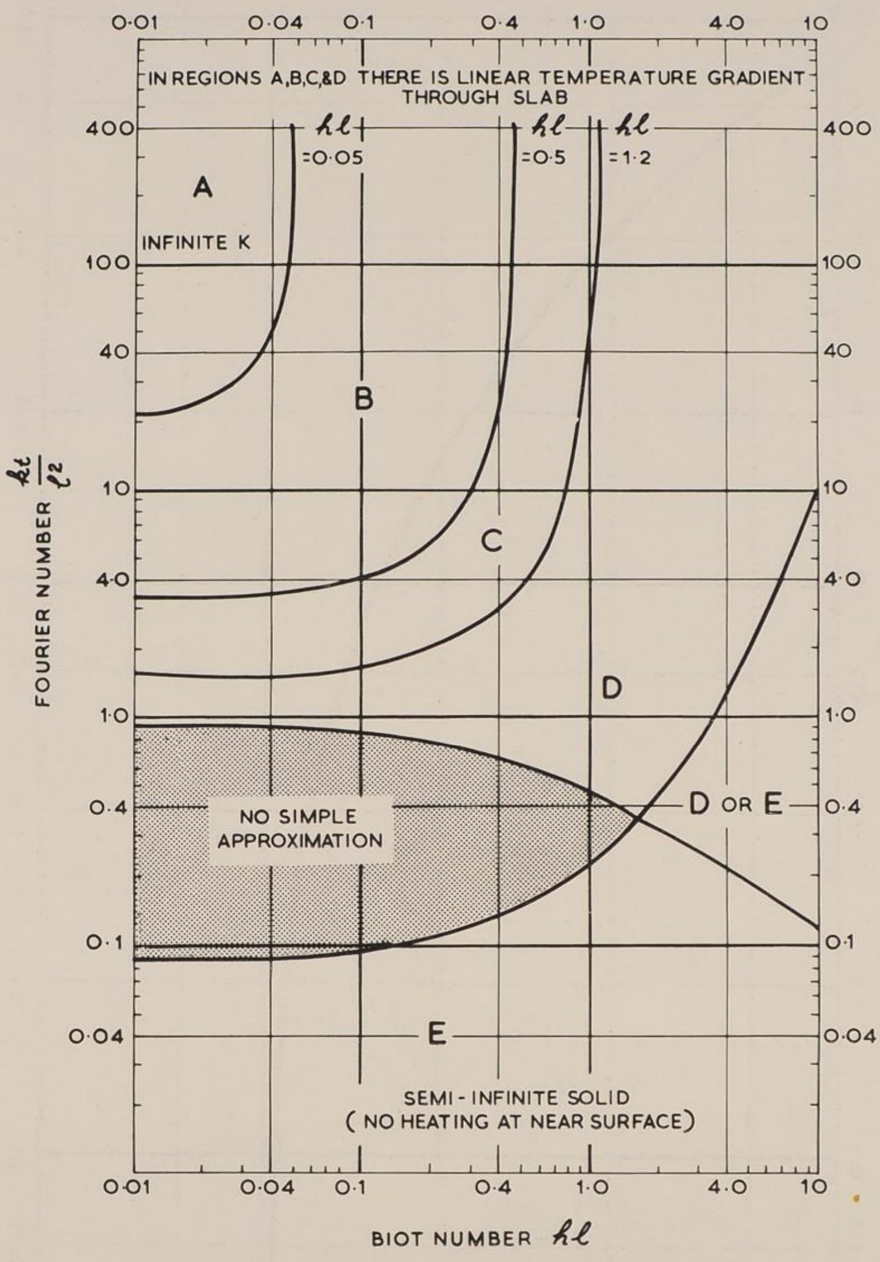

ROLE OF DIMENSIONLESS GROUPS IN
DETERMINING SURFACE TEMPERATURE RISE

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PART VI
CHAPTER 3
SECTION 3.3
FIGURE 2

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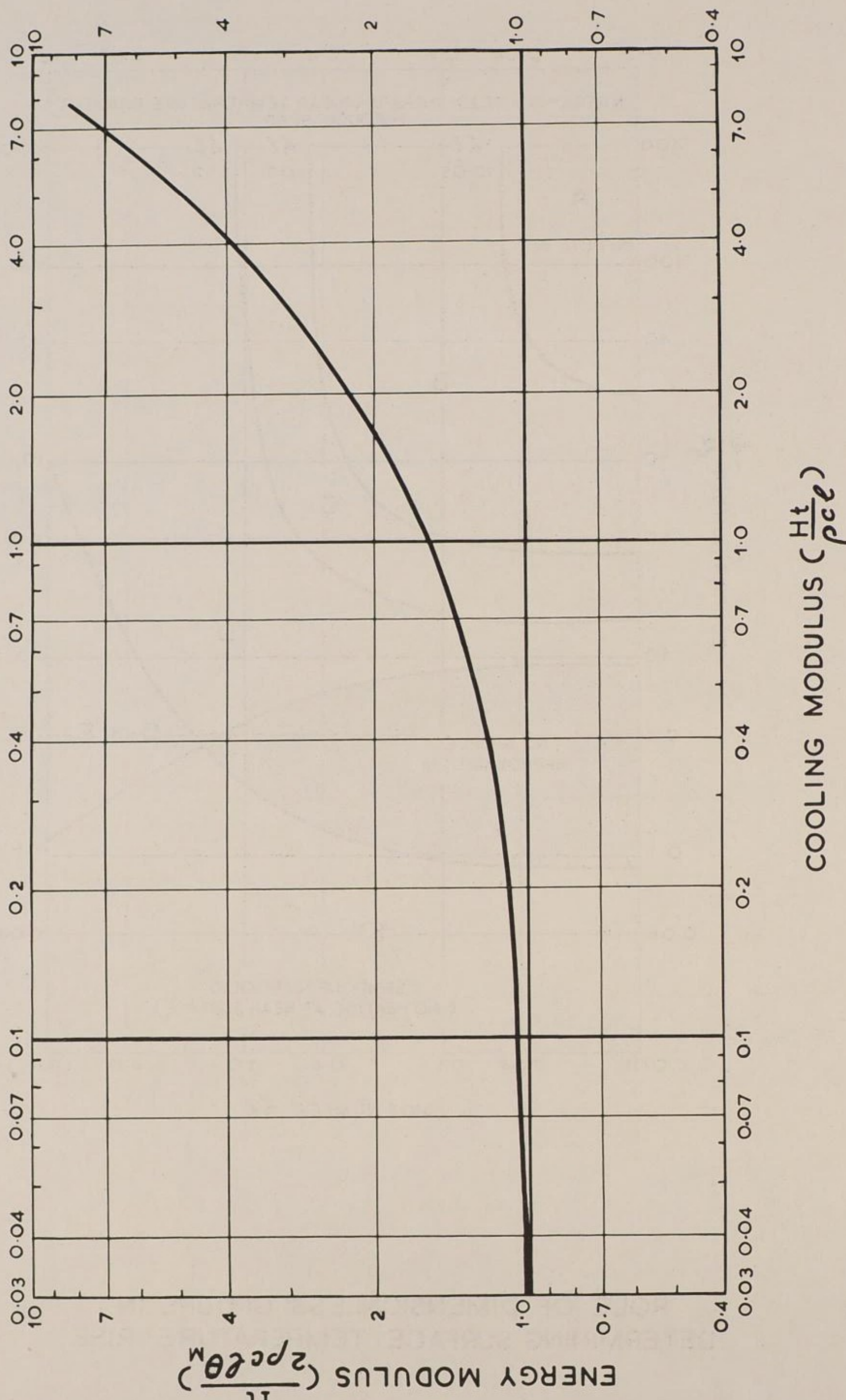

THEORETICAL VALUE OF MEAN TEMPERATURE RISE
FOR A SLAB WITH LINEAR TEMPERATURE GRADIENT

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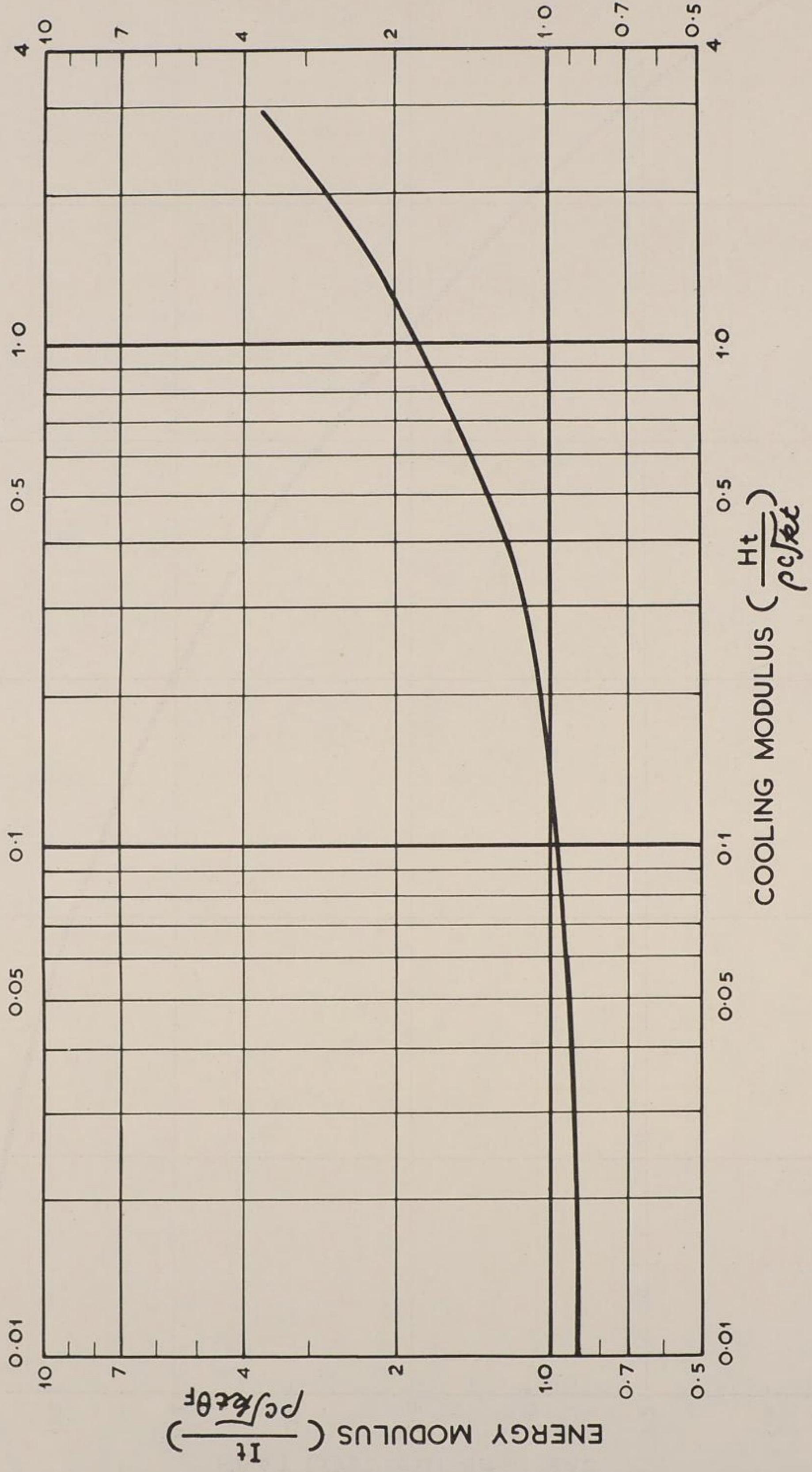

THEORETICAL VALUE OF SURFACE TEMPERATURE RISE
OF AN IRRADIATED SEMI - INFINITE SOLID

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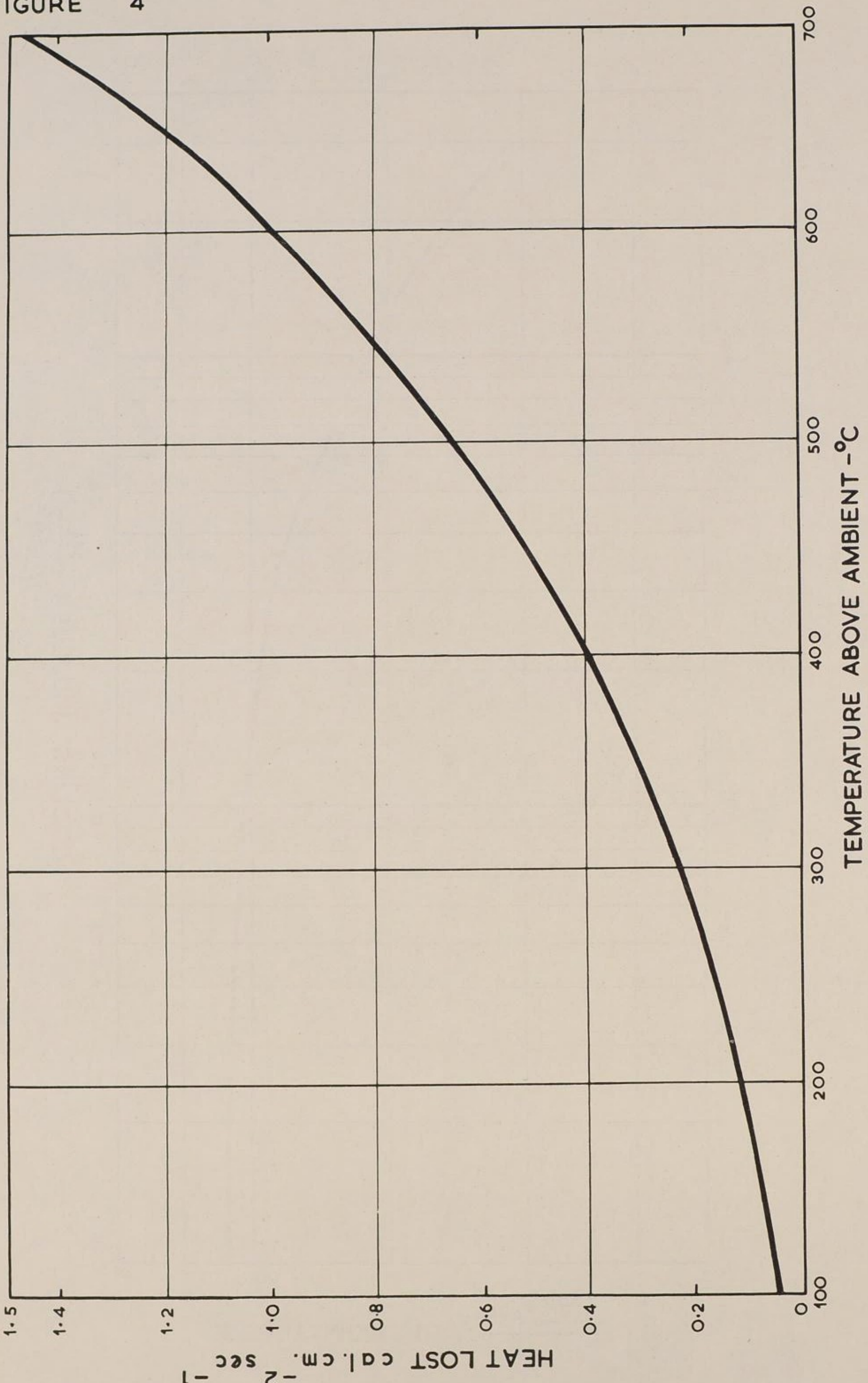
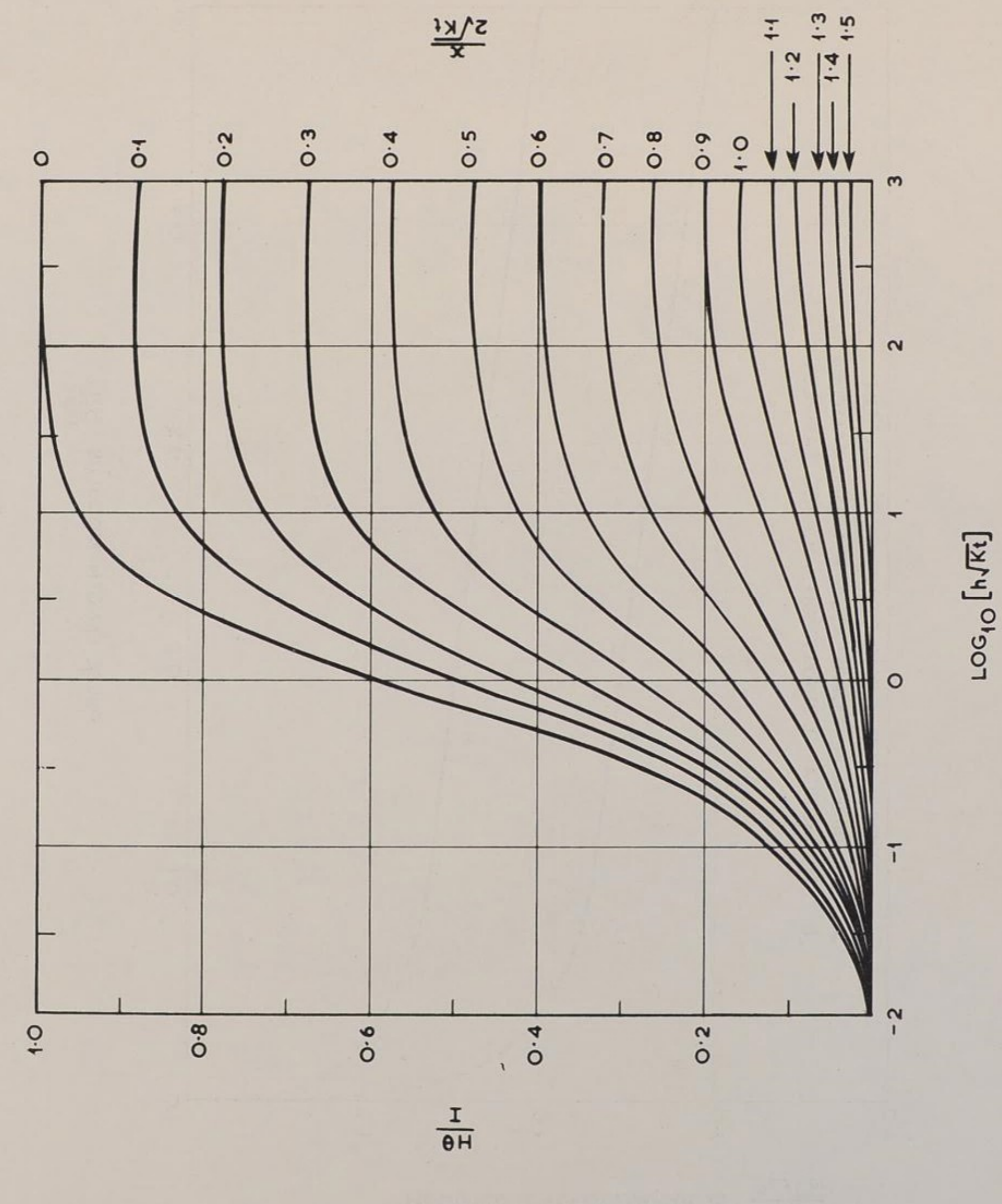


RADIATION AND CONVECTION LOSSES FROM A HOT BODY TO AN AMBIENT TEMPERATURE OF 17° C



TEMPERATURE DISTRIBUTION IN THE SEMI-INFINITE SOLID WITH RADIATION AT ITS SURFACE

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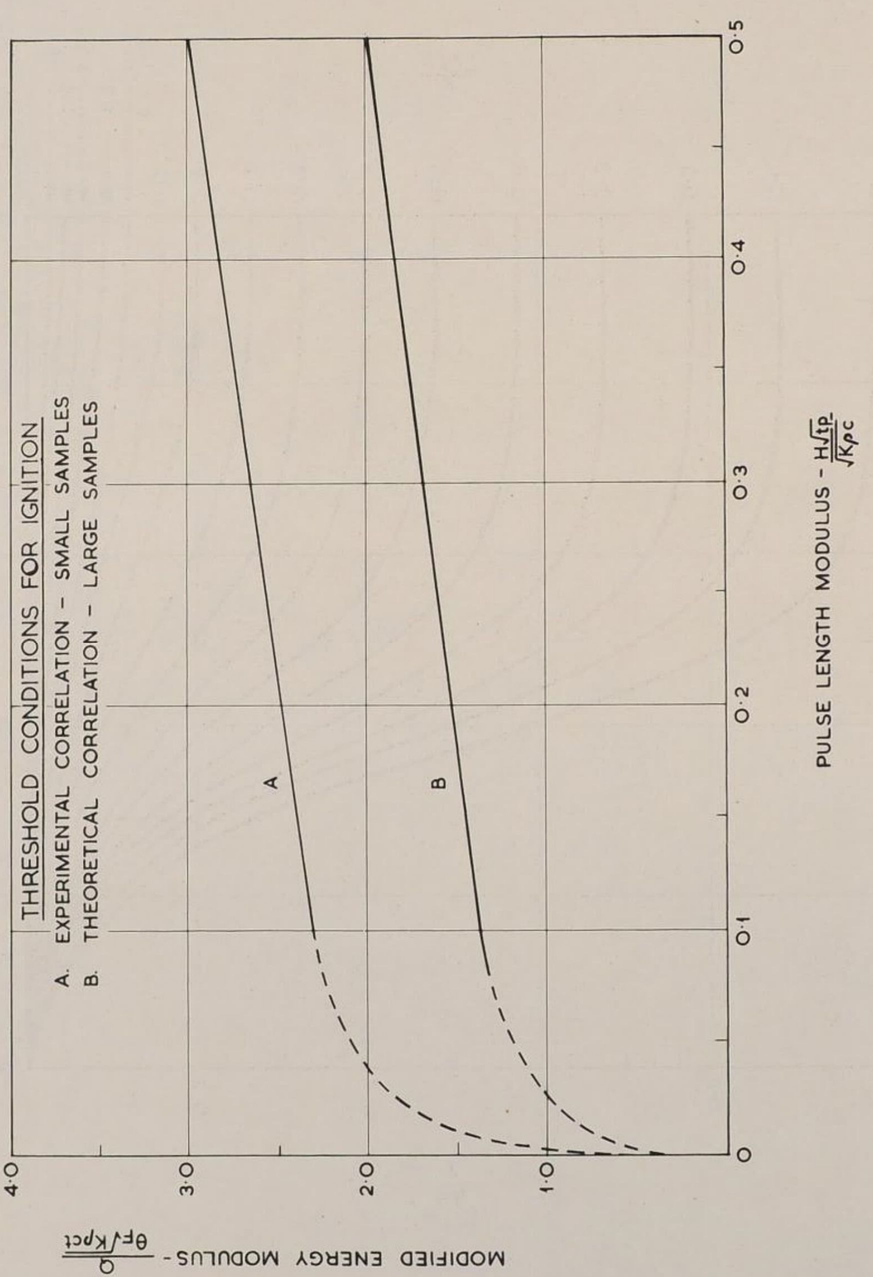

THE SURFACE TEMPERATURE RISE OF AN IRRADIATED SEMI-INFINITE SOLID

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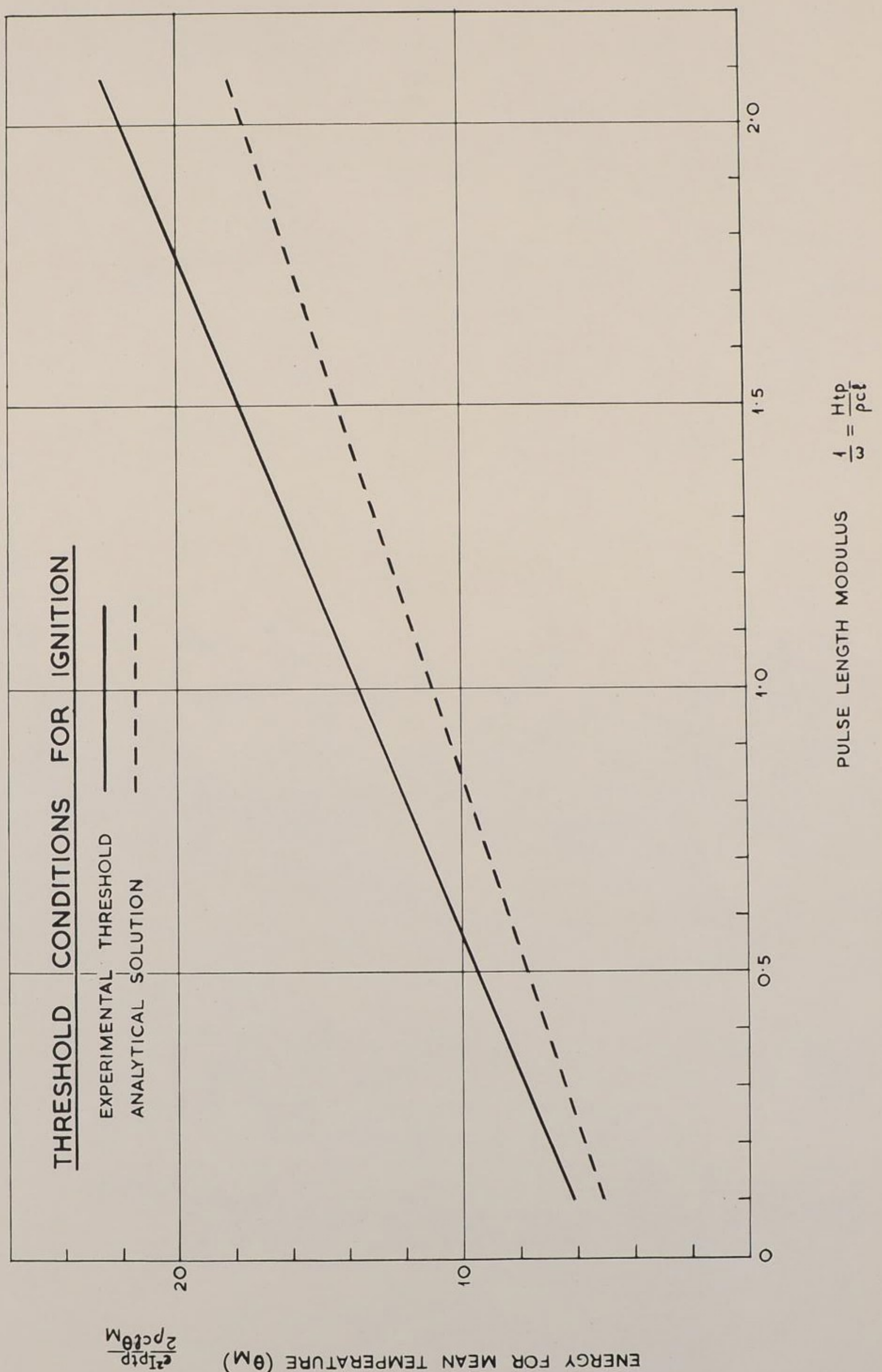


THE MEAN TEMPERATURE OF A SLAB
WITH LINEAR TEMPERATURE GRADIENT

CONFIDENTIAL

CHAPTER 4 - THERMAL EFFECTS ON MATERIALS

Chapter 3 enables the effect of temperature-time patterns in irradiated materials to be estimated. Most materials are not inert and various kinds of thermal damage can occur, depending upon the rate and time of heating. Combustible materials may char, crack, melt, and ignite with a flame which may or may not persist. Non-combustible materials may melt, crack, shatter, or lose strength. It is not yet possible to give criteria for all these effects, but some available data are presented in this Chapter.

4.1. Thermal Damage to Combustible Materials

When radiation falls on the surface of a combustible material, the temperature at the surface and throughout the material rises in a way and at a rate depending upon the factors listed in Chapter 3.

In the surface region, the rise in temperature beyond 100°C is temporarily checked until the moisture has been driven off. In the common organic materials, mainly cellulose and its derivatives, a chemical reaction begins at about 180°C, scorching or charring the surface. This reaction may become extremely rapid at about 250°C. If the rate of heating is fast enough to produce volatiles, which form a flammable mixture with air, then the surface of the material bursts into flames, which may or may not persist. If a subsidiary ignition source is available, then a far lower rate of heating may be sufficient to cause ignition (Reference 1)). Many plastic materials, e.g. nylon, perspex, terylene, melt at about 200°C.

Thus, depending upon the time of exposure and the intensity of radiation, a given material may char, melt or ignite with or without persisting flame. Most of the work carried out in this country has been concerned with fire research and has therefore used radiation characteristic of a temperature of 1100°K (Reference (1)), but apparatus is now available (Reference (2)) to study the effects of using radiation of the quality of a nuclear explosion. A device for producing impulses of energy of shapes corresponding to any weapon yield, has also been developed.

The correlation of thermal damage - A method has been developed at the Fire Research Station for the correlation of thermal damage (References (3),(4),(5),(6),(7)). The temperature rise is calculated on the assumption that the material is thermally inert, and dimensionless groups are derived to express the thermal parameters (see Figure 6 of Section 3.3, Chapter 3). Satisfactory correlations between theoretically derived curves and threshold conditions for ignition have been obtained using an ignition temperature of 525°C (Reference (5)). Similarly, correlations between field and laboratory data for charring have been obtained using a charring temperature of 300°C (Reference (6)). Results from both British and U.S. field trials on the total destruction of fabrics have also been correlated, (Reference (7)), and are shown in Figure 1.

Similar techniques could be applied to assess thermal damage in other irradiation problems.

Estimates of the effect of moisture content on the ignition of wood have also been made (Reference (8)). The effect appears to be small for ignition by nuclear explosions (Reference (9)), though it may reduce the chance of a continuing fire being started.

A general survey of the problem is given in the publication "Fire and the Atomic Bomb" (Reference (10)).

References

(1) Lawson, D. I., and Simms, D. L. "The Ignition of Wood by Radiation". British Journal of Applied Physics, 1952. Vol. 3, pp. 288-292.

(2) Hinkley, P. L. "High Intensity Radiation from a Carbon Arc Ellipsoidal Mirror". Joint Fire Research Organisation. R.R. Note No. 270/1957. Ibid, Part II. "The Shape of the Pulse of Radiation". S.R. Note No. 29/1957. (Secret)

(3) Simms, D. L. "The Correlation of Ignition Time with the Physical Properties of Materials". Part I. "Spontaneous Ignition of Cellulosic Materials". J.F.R.O., F.R. Note No. 319/1957.

(4) Thomas, P. H., and Simms, D. L. "Thermal Damage to Solids by Radiation and Chemical Decomposition". J.F.R.O. F.R. Note No. 331/1958.

(5) Thomas, P. H., Simms, D. L. and Law, Margaret. "The correlation of the threshold for ignition by radiation with the physical properties of materials". J.F.R.O. F.R. Note No. 381/1958.

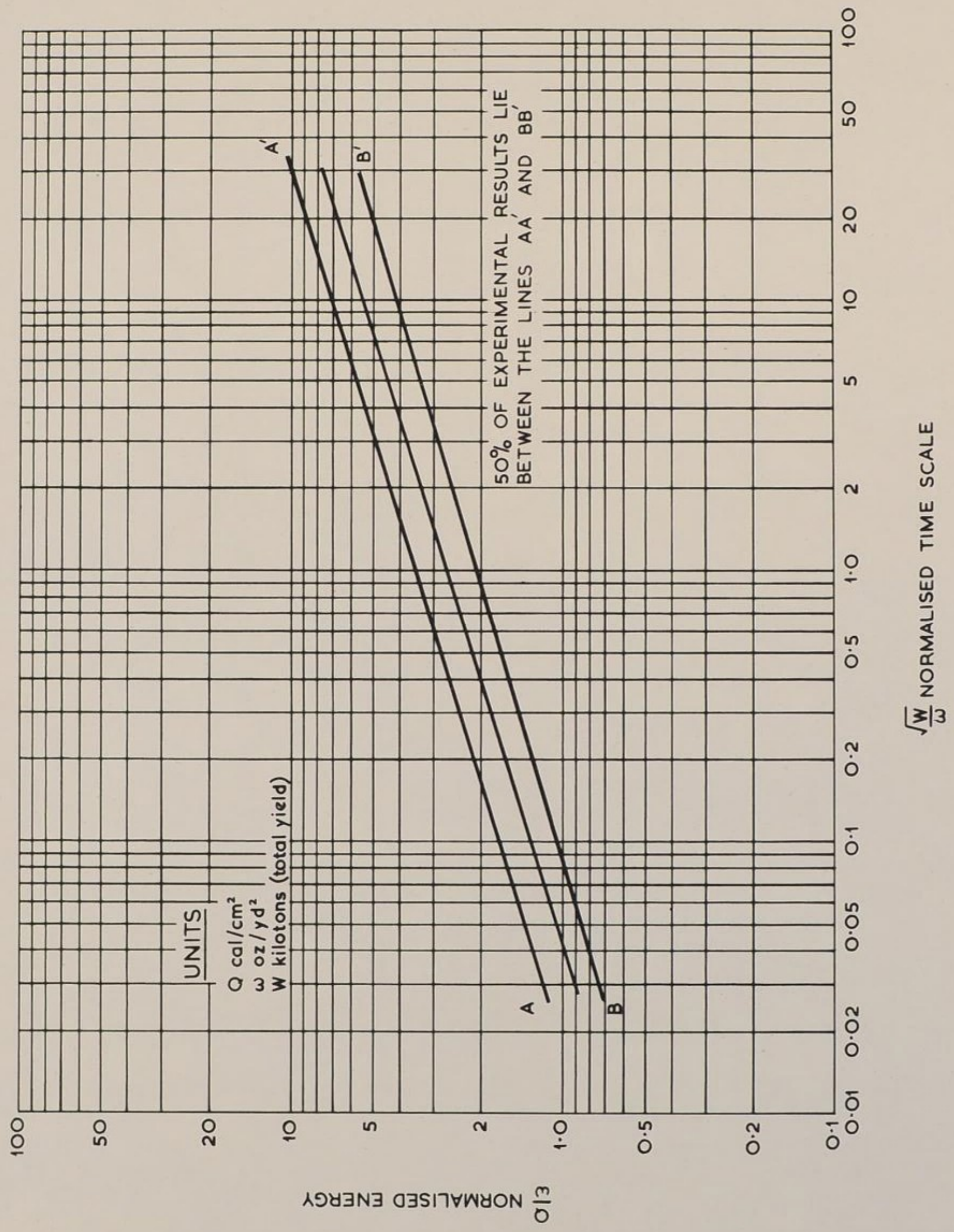
(6) McGuire, J. H., Smith, P. G., and Thomas, P. H., "Correlation of Field and Laboratory Tests on the Exposure of Fabrics to Radiation". J.F.R.O. S.R. Note No. 37/1958 (Secret)

(7) Thomas, P. H., and Simms, D. L., Correlation of field data for the total destruction of fabrics by nuclear explosions. J.F.R.O. S.R. Note No. 36/1958. (Confidential)

(8) Thomas, P. J., Simms, D. L., and Law, Margaret, "The Effect of Moisture Content on the Ignition of Materials by Radiation". J.F.R.O. F.R. Note No. 280/1956.

(9) Simms, D. L. and Law, Margaret. "The Effect of Moisture Content on the Ignition of Materials by an Atomic Explosion" J.F.R.O. S.R. Note No. 31/1957. (Restricted)

(10) Lawson, D. I. "Fire and the Atomic Bomb". Fire Research Bulletin No. 1, H. M. Stationery Office, 1954.



CORRELATION FOR TOTAL DESTRUCTION OF FABRICS
BY THERMAL RADIATION

4.2. Critical Energy Data for Combustible Materials

4.2.1. Textiles

Small specimens of various textiles were exposed at Operation Buffalo to the heat flash from Round I (about 15 KT), and the extent of the damage observed is summarised briefly in Table I, for a selection of the materials used. The following general conclusions are made in Reference (1) from consideration of the extensive thermal data obtained at Operation Buffalo.

(i) Materials which decompose without melting, or before melting begins (e.g. cotton, wool, etc.) afford better protection to the underlying skin that those that melt or are softened on exposure to heat (e.g. nylon, polyvinylchloride and synthetic fibres generally).

(ii) Resistance to damage by thermal radiation generally increases with increasing weight per unit area of the material, and several layers are much superior in this respect to a single layer of the same total weight.

(iii) White or light-coloured materials suffer less damage than dark materials, but thin white materials transmit the radiation to the underlying layers more readily than do dark-coloured materials. Thin white materials in contact with black underlying layers are damaged by heat sooner than when the underlayer is white.

(iv) In fabrics composed of a mixture of cotton and nylon there is an indication that resistance to damage is slightly reduced by the presence of nylon, owing to acceleration of the rate at which heat damage occurs.

(v) Terylene only improves the heat resistance of wool marginally.

(vi) Flameproofing does not affect the flashing of fabrics.

In Table 2 (taken from Reference (2)), the critical radiant exposures for specified damage to various fabrics are shown for three weapon yields. These values apply for an ambient relative humidity of 65% and an ambient temperature of 20°C. For extremely dry conditions the values shown for fabrics should be reduced by 20%. For extremely high relative humidity, near 100% at 20°C, the values for fabrics should be increased by 25%. If the fabrics are water soaked, the critical radiant exposures should be increased by 300%. It should be emphasized that the values in Table 2 for uniforms refer to damage to the material itself, and are not applicable for predicting skin burns under uniforms.

A correlation of these results is shown in Figure 1 of Section 4.1, from which the threshold conditions for damage to other materials may be estimated, (Reference (3)). White materials require about twice as much energy for total destruction as other materials. There does not appear to be any significant difference between different types of material, sizes of bomb, or origins of results.

References

(1) A.W.R.E. Report T12/58. Operation Buffalo Target Response Tests, Materials Group. Part 2: "Effects on Textiles". (Confidential)

(2) Capabilities of Atomic Weapons. U.S. Department of the Army. TM23-200 p.12-3 (Confidential)

(3) Thomas, P. H. and Simms, D. L., "Correlation of field data for total destruction of fabrics by nuclear explosions." Joint Fire Research Organisation". S.R. Note No. 36/1958. (Confidential)

TABLE I - Damage to Miscellaneous Textiles by Thermal Radiation from an Approximately 15 KT Weapon

Material	Thickness in.x 10^{-3}	Weight oz/yd^2	Calories/cm^2		
			Incipient damage	Serviceability just retained	Total Destruction
Cotton duck, water-proofed, olive drab	26	15	6	12	24
ditto, fireproofed	29	22.4	8	12	48
Cotton canvas, plain olive drab	37	24.1	3	16	32
ditto, waterproof	39	24.7	4	64	>128
Hessian, brown	64	12.4	4	8	32
" green	58	12.6	3	8	16
" black	63	13.1	4	6	16
100% wool, cavalry twill fawn	52	14.3	3	6	>48
15% nylon, flannel grey	22	6.6	3	3	12
50% nylon, flannel grey	20	5.3	2-3	2	12
100% nylon, plain weave fawn	20	7.2	8	8	16
100% wool twill, white	28	9.0	4	12	32
20% terylene wool twill white	25	8.6	12	24	32
60% " " "	22	7.8	12	16	24
100% terylene twill white	19	7.6	8	8	24
100% cotton plain cloth pale blue	10	5.1	8	16-24	32
32% nylon " "	10	5.1	12	16	24
Serge battledress, khaki	50	14.5	4	12	32
Sateen combat suit, olive drab	20	8.8	4	6	24
Drill, cotton, khaki	23	7.3	6	6	12

TABLE 2 - Critical Radiant Exposure Values for Various Fabrics
(S = Scorched, D = Destroyed)

Uniforms	Colour	Weight (oz/yd^2)	Damage	Critical Radiant Exposure $cals/cm^2$ 1 KT	100 KT	10 MT
Army						
Cotton twill fatigue	Green	8	S	3	5	9
			D	8	14	25
Wool serge (winter service)	Olive Drab	9	S	3	6	10
			D	21	37	66
Wool flannel	Olive Drab	11	S	3	5	8
			D	20	40	70
Wool tropical worsted	Khaki	11	S	6	9	13
			D	13	20	30
Cotton twill shirt and trousers (summer)	Khaki	6	S	4	6	11
			D	18	31	56
Navy						
Cotton twill (working)	Khaki	8	S	3	5	8
			D	15	26	46
Cotton denim (dungaree)	Blue	9	Nap S	6	10	17
			D	7	13	23
Cotton chambray shirting (working)	Blue	3	S	3	6	11
			D	7	13	22
Cotton twill (white uniform)	White	8	S	4	8	14
			D	34	60	109
Wool, Melton (dress blues)	Blue	16	S	1	16	13
			D	9	18	28
Wool, Kersey (overcoat)	Blue	30	S	1	2	3
			D	37	65	110
Wool, serge (officer's uniform)	Blue	14	S	5	9	16
			D	11	21	37
Wool, tropical worsted (officers' uniform)	Khaki	11	S	5	9	16
			D	11	20	37
Vinyl resin, combined (rain)	Black	13	S	1	1	2
			D	5	6	8
Marine Corps						
Cotton poplin shirting	Olive Drab	6	S	3	6	10
			D	10	18	32
Wool elastique (winter)	Green	16	S	2	4	7
			D	25	45	80
		21	S	5	8	15
			D	30	54	95
Wool, Kersey (winter)	Green	16	S	2	3	6
			D	27	48	85
Wool, serge	Green	12	S	2	3	6
			D	16	28	50

TABLE 2 (Contd.)

Uniforms	Colour	Weight (oz/yd^2)	Damage	Critical Radiant Exposure cals/cm^2		
				1 KT	100 KT	10 MT
Air Force						
Cotton twill shirt	Khaki	5	S	6	10	19
(tropical)			D	9	15	27
Wool gabardine shirt	Grey	8	S	10	17	28
			D	14	22	37
Wool gabardine shirt	Blue	8	S	1	2	4
			D	8	14	25
Nylon - flying jacket	Olive	5	S	2	3	6
	Drab		D	7	13	23

4.2.2. Plastics

Small specimens of various plastics were exposed at a number of sites at Operation Buffalo to the heat flash from an approximately 15 KT explosion (Reference (1)). The types of materials used were:-

1. Polythene sheet, low and high pressure variety, normal, black, and irradiated (thickness 0.061-0.069 inch).

2. Polyvinylchloride sheet of varying colour and platiciser content (thickness 0.059-0.085 inch).

3. Nylon sheet of varying grade and colour (thickness 0.128-0.131 inch).

4. Phenolic mouldings and laminates with various fillers (thickness 0.060-0.121 inch).

5. Glass fibre resin laminates. Different resins. (Thickness 0.061-0.069 inch).

6. High impact polystyrene, varying colours and fillers (thickness 0.065-0.151 inch).

7. Polytetrafluorethylene (P.T.F.E.) (thickness 0.126 inch).

8. Polychlorotrifluorethylene (P.C.T.F.E.) (thickness 0.058 inch).

After exposure, the samples were examined visually and mechanical tests were carried out where possible. The tests employed were tensile strength and elongation at break, flexural strength in 3-point bending, shear strength and hardness. Full details of these plastics and the mechanical test results are given in Reference (1).

The results obtained are based on only one specimen exposed at each site. Some anomalies may therefore be expected in the results owing to the variability of the materials themselves and to damage which may have arisen due to the positioning. Nevertheless, there are definite trends in the results, and some general conclusions can be drawn.

(i) The plastic materials generally withstood the exposure conditions rather better than would have been expected from consideration of their stability when heated at low intensities for long periods. In the group of thermo-plastic materials, the relative performance of the high and low softening point polymers was comparable.

(ii) Colour affected the behaviour of the specimens. In general, the black materials embrittled at much lower calorie doses than the light-coloured samples. The effects on the natural polymers, normally off-white in colour, and of those formulations containing white pigment, were very similar.

(iii) In the case of phenolic mouldings and laminates, the type of filler influenced the results. The glass and asbestos-filled laminates were least affected. The silver-coloured high impact polystyrene (filled with aluminium powder) was more distorted than other polystyrene samples, but the fall in flexural strength was of the same order.

(iv) The materials least affected by the exposure were the fluorine containing polymers P.T.F.E. and P.C.T.F.E., and some of the glass-fibre resin laminates. These samples were only slightly marked at the maximum thermal flux of 128 cals/cm^2. The fire-resistant polyester glass-fibre laminates however, showed some surface deterioration in the range 32-48 cals/cm^2, and a drop in flexural strength of 30% at a dose of 96 cals/cm^2.

(v) For the majority of the materials the critical point for visual surface damage was in the range 12-24 cals/cm^2. At thermal fluxes below this level, slight changes in the surface texture such as bleaching, polishing, or delineation of the exposure area, were evident in many oases. By visual assessment, the materials could be rated according to the thermal flux at which marked surface deterioration first occurred. It is evident from the results of the mechanical tests however, that the damage was, in the main, confined to the surface, and that the bulk of the material was unaffected. This is understandable in view of the poor thermal conductivity of plastics in general.

Some American data from Reference (2), on the behaviour of certain plastics to thermal radiation from nuclear explosions, is given in Table I below.

TABLE I

Material	Damage	Critical Radiant Exposure calories/cm^2		
		1 KT	100 KT	10 MT
Laminated methyl methacrylate	Surface melts	73	120	230
U.S.A.F. window plastic (½ inch)	Bubbling	240	430	750
Vinylite (opaque) (⅛ inch thick)	(Dense smoking (Flaming	3 20	4 20	6 25

References

(1) A.W.R.E. Report T18/58. Operation Buffalo Target Response Tests, Materials Group, Part 3 : Effects on Plastics. (Confidential)

(2) Capabilities of Atomic Weapons. U.S. Department of the Army, TM 23-200, page 12-4. (Confidential)

4.2.3. Rubbers

Service and civilian respirator rubbers were exposed at Operation Totem, and the results are summarised in Table I (Reference (1).

TABLE I - Effects of Thermal Radiation on Respirator Rubbers

Material	Total Incident Thermal Energy, cal/cm^2				
	7	11	21	35	63
G.S. Respirator rubber (1.9 mm thick)	Not Exposed	Flashed, Surface-melted	Flashed and burned	Flashed and burned fiercely	Flashed and burned fiercely
Civilian Respirator rubber (0.9 mm thick)	Very slight melting on front surface	Flashed, Surface-melted	Flashed and burned	Flashed and burned fiercely	Flashed and burned fiercely

This trial demonstrated that the risk to the wearer of a Service respirator of being burned by heat conduction through the rubber, was slight, but that there was some danger of this happening with the civilian respirator. The eye-piece of the Service respirator transmitted about 60% of the incident radiation; consequently the eyes and the areas surrounding the eyes will be susceptible to serious burn injury from explosions occurring in front of the wearer, at ranges beyond those corresponding to significant respirator damage. (See Chapter 7, Sections 7.2 and 7.8).

At Operation Buffalo, specimens of various types of rubbers were exposed to the thermal flash from an approximately 15 KT weapon (Reference (2)). A comparison was made of the behaviour of four rubbers - natural, polychloroprene, butadiene acrylonitrile (nitrile) and butadiene isoprene (butyl).

Each rubber was represented by specimens in three colours - black, white, and olive drab. Specimens of heavy and light cotton fabrics proofed with natural rubber and neoprene compounds, were exposed in order to assess the behaviour of relatively thin coatings of rubber.

The most obvious effect of exposure on the four types of mechanical rubber was contamination by desert sand of the specimens at the sites nearest to ground zero. This was apparently the result of thermal softening of the surface of the rubber, to which sand adhered through the ensuing blast. The heaviest contamination occurred mainly at a thermal dose of 96 cals/cm^2, rapidly decreasing with lower doses, and not occurring at all doses of less than 6 cals/cm^2. The colour of the rubbers also affected the surface contamination, which decreased in the order black, olive drab, white.

Mechanical tests (tensile strength and elongation at break) were carried out on many of the exposed specimens, with the results summarised briefly below.

Natural Rubber - The effect of thermal dose was less noticeable with increasing carbon black loading, and at the highest loading (100 parts black per 100 parts rubber) there was no significant effect attributable to heat. In the white and olive drab samples the effect of thermal dose was very slight and was less in the case of olive drab than of white samples.

Polychloroprene Rubber - Elongation at break appeared to be little affected by thermal dose, but there was marked reduction of the tensile strength of the black specimens at thermal doses above 6 $cals/cm^2$. It was considered however, that all the samples would have been serviceable for reasonably long periods. There was no significant effect on any of the white samples, nor on the olive drab samples exposed to doses of 64 $cals/cm^2$ or less.

Nitrile Rubber - The effect of exposure on the elongation at break and tensile strength of the black nitrile rubbers was of little significance at thermal doses below 128 $cals/cm^2$, and although there was some reduction at this figure (the highest thermal dose) the results were still within specification limits. Anomalous results however, were obtained with the white and olive drab samples, the elongation at break and tensile strength improving with increasing thermal dose up to 32 $cals/cm^2$, followed by a very slight fall. It is considered that the white samples would have been unusable, but that the olive drab would be capable of very limited use.

Butyl Rubber - In no case was there any significant effect on the elongation at break. On tensile strength, there was a marked effect at thermal doses of 96 $cals/cm^2$ and above, but at doses lower than this the results showed hardly any significant change. It is considered that all the samples would still have been serviceable.

The general conclusion drawn from the examination and testing of specimens is that the nature of the polymer and the colour of the material are the two main factors which influence degradation. On a colour basis, the rubbers displayed increasing resistance to thermal radiation, from white through olive drab, to black, (i.e. black samples most resistant). Of the polymers exposed, natural rubber showed the best resistance, followed by butyl and polychloroprene, with nitrile rubbers as the most seriously affected.

References

(1) A.W.R.E. Report T77/54. Effects on Respirators Anti-Gas. (Confidential)

(2) A.W.R.E. Report T16/58. Operation Buffalo. Target Response Tests. Materials Group, Part 4 : Effects on Rubbers. (Confidential)

4.2.4. Packaging Materials

Small specimens of sheet packaging materials were exposed to the heat flash from an approximately 15 KT weapon at a number of sites at Operation Buffalo. Multi-wall and hessian sacks filled with sand, lengths of rope of various fibres, and thermal screens of ground sheets and camouflage nets, were exposed to both heat and blast at several sites. Full details of the results will be found in Reference (1), but a summary of the main conclusions is given below.

Sacks - Sacks made of laminates of Kraft and bitumen Kraft union showed increasing depth of damage with increasing heat dose. The outer laminates were almost completely destroyed before the inner laminates were seriously affected. This survival of the lower layers indicates the value of a thermal screen built up of inflammable sheets supported by thin air gaps, and is confirmed by the damage sustained by the uncovered sand-filled hessian sacks. None of the paper sacks was holed by the heat flash up to a dose of 24 cals/cm^2, while the hessian sacks had spilled contents at 16 cals/cm^2. Temperature indicators which were placed behind the specimens in the exposure frames, recorded no temperature rise above 80°C behind the Kraft laminates on any site, while the temperature rose to at least 100°C at the 8 calorie site, increasing to 170°C at 48 calories, behind the hessian with a cotton underlayer, and to 140°C and 190°C at the same sites behind a single hessian layer.

Tarpaulins - Tarpaulins gave excellent protection against heat to all sacks with which they were placed, on sites where blast did not cause additional damage, but tentage similarly placed, caused more damage through catching fire than resulted from the heat flash alone.

Fibre Boards - Carton board and corrugated board showed the value of air-spaced laminates in a manner similar to that shown by the sacking. The building paper Sisalkraft and polymer transparent sheets showed a resistance to heat damage consistent with their construction, but the value of a metal foil coating in protecting paper from heat damage was very striking.

Timbers - There was no difference in the degree of burning shown by planed and unplaned samples of the same wood. The hard woods were slightly more sensitive to incipient scorching (at 8-12 cals/cm^2) than the soft woods, but were less deeply charred at the higher heat doses (up to 128 cals/cm^2).

Spray-Packaging Materials - A skin made solely from the vinyl plastics used for short-term packaging, suffered complete destruction at only 6 cals/cm^2, while the vinyl/bitumen skin with aluminium paint used for full protection suffered only surface damage up to at least 64 cals/cm^2, after which the specimens were torn by blast.

Ropes - The sisal ropes, both untreated and rot-proofed, showed some scorching after 8-12 cals/cm^2, but did not materially lose strength until the thermal dose exceeded 24 cals/cm^2, when the breaking loads showed an erratic loss of strength of about 20% to 30%, probably due to blast rather than heat. The terylene and nylon ropes showed no damage at thermal doses below 12 cals/cm^2. At higher doses, there was a proportional increase in loss of strength up to 50% at about 100 cals/cm^2, with corresponding signs of fusing of the polymer fibres.

References

(1) A.W.R.E. Report No. T29/58 Operation Buffalo Target Response Tests. Materials Group, Part 7. "Effects on Packaging Materials". (Confidential)

4.2.5. Paints

Samples of paints of formulations selected for heat resistance were applied to small plates of various metals, and exposed to the heat flash from a weapon of about 15 KT at Operation Buffalo. (Reference (1)).

Paint films applied to steel plates had the following formulations:-

(a) 1 coat green. Epoxide resin araldite 985E

(b) 1 coat aluminium. Epoxide resin araldite 985E

(c) 1 coat primer. Zinc pigmented butyl titanate
1 top coat. Aluminium pigmented butyl titanate.

(d) 1 coat green. Silicone resin.

(e) 1 coat aluminium. Silicone resin.

(f) 1 coat green. Silicone alkyd.

(g) 1 coat aluminium. Silicone alkyd.

(h) 1 coat primer DEF 1035
1 coat undercoat DEF 1044
1 top coat DEF 1044 green

(j) 1 coat primer DEF 1035
1 coat undercoat DEF 1044
1 top coat DEF 1044 type alkyd medium, aluminium

(k) 1 coat aluminium paint to CS 1199.

(l) 1 coat "Alifuse". Zinc/aluminium pigmented butyl titanate

No change in the paint layers was visible on specimens receiving heat doses up to 12 cals/cm^2. Some of the specimens on the sites nearest the ground zero were scattered by blast and not recovered. The remainder of the specimens showed the effects described in Table 1 below.

TABLE I

Thermal Damage to Paints on Steel Plates

Paint	Incident Thermal Dose (Cals/cm^2)						
	16	24	32	48	64	96	128
a. Epoxide Green	NC	NC	NC	Sl.loss	-	-	-
b. Epoxide	NC	Sl.Dc.	Sl.Dc.	Sl.Dc.	Marked Dc.	Marked Dc.	Film mechanically damaged.
c. But. Titanate 2 coats	NC	V.sl. Dc.	Sl.Dc.	Marked Dc.	Marked Dc.	-	Heavy Dc.
d. Silicone Resin Green	NC	NC	NC	Sl.Dc.	Sl.colour change Blistered	Marked darkng. Blistered	Film almost completely destroyed
e. Silicone Resin Aluminium	NC	NC	V.Sl. Dc.	Marked Dc.	Marked Dc.	Marked Dc. Pitted	Marked Dc. Pitted
f. Silicone Alkyd Green	NC	NC	NC	Darkng sl. blistering	As 48	As 48	As 48 Brown stain
g. Silicone Alkyd Aluminium	NC	NC	V.Sl. Dc.	Sl.Dc. some pitting	Marked Dc. some pitting	As 64	As 64
h. DEF 1044 Green	V.sl. darkng.	Sl. darkng.	Severe darkng.	Blackened	Blackened Erosion	-	Dark grey Erosion
j. DEF 1044 Aluminium	NC	NC	V.sl. Dc.	Marked Dc.	Marked Dc. some pitting	-	Marked Dc. Some pitting
k. CS 1199 Aluminium	NC	V.sl. Dc.	V.sl. Dc.	-	Sl.Dc. pitting	As 64	As 64
l. "Alifuse"	V.sl. Dc.	NC	V.sl. Dc.	Marked Dc. Pitting	Sl. Dc. pitting	As 64	As 64

NC = No change
Dc = Discolouration
V = Very
Sl = Slight

None of the paints listed in Table 1 showed any effect from heat doses below 16 cals/cm^2. Results at higher doses indicated that:-

1. A paint pigmented with aluminium is more resistant to heat flash than one with a green pigment.

2. Of all the paints exposed, those based on butyl titanate show greatest resistance to heat flash.

3. In comparing paints made from epoxide "araldite" resin, silicone resin, and silicone alkyd, the epoxide resin paints showed greatest resistance to heat flash.

In an additional series of tests at Operation Buffalo, specimens of paints applied to magnesium, titanium, steel and aluminium alloy plates were exposed to thermal flash of various intensities from a 15 KT explosion. Strips of heat-sensitive paints were applied to the backs of the plates to record the maximum temperature reached. Most of the specimens were samples of standard aircraft paint schemes. There were also some unpainted samples of polished metals, including silver plated steel and electro-polished aluminium ("Brytal"). Many of the plates located on sites receiving 96 and 64 cals/cm^2 were blown away, and those reamining were badly damaged by sand blasting. This prevented any precise appraisal of thermal damage, but generally the white paints were unaffected, whereas silver paints (i.e. aluminium pigments) showed obvious blistering. From sites receiving 48 and 32 cals/cm^2, the white and silver paints did not show any thermal damage, as the dose was insufficient to affect them. However, the brown-painted samples from these sites were severely burned.

References

(1) A.W.R.E. Report T27/58. Operation Buffalo Target Response Tests, Materials Group. Part 5 : Effects on Paints. (Confidential)

4.3 Absorption of Heat by Metallic Surfaces

The procedure for estimating the thermal dose to a surface is given in Section 1.3 of Chapter 1, and a discussion of the factors which influence the temperature rise of irradiated materials is given in Chapter 3. Some values of the temperature rise of irradiated surfaces have been obtained (References (3)).

Absorption data for sunlight and carbon arc radiation are presented in the following sections. The figures give a good general picture of what the initial absorption of fireball radiation is likely to be, but they should not be used for refined calculations. In particular, they do not indicate any change of absorption coefficient with dose absorbed. Ideally, we require relationships between the total incident does and total dose absorbed for each surface. As such data are not yet available, the present data are provided as an interim measure.

4.3.1. Absorption by Bare Metallic Surfaces

The absorptivity of a polished metal surface will be increased by roughening, and by dirt or corrosion. The influence of the state of the surface (polished or rough, oxidised or machined, etc.) can be seen from Table 1 below, which is taken from Reference (1). Whereas a trace of oxide (tarnishing) does not appreciably change the absorptivity, thick oxide layers raise it considerably. Heavily oxidised and very rough surfaces approach the behaviour of a black body. The values given in Table 1 may hold up to 200°C. For higher temperatures, too, they will not change much.

Table 1

Influence of the State of Surface of Metals upon the Absorptivity at 25°C

Substance	State of Surface	Percent Absorptivity
Copper	Polished	3
	Polished, slightly tarnished	3.5
	Shaved	7
	Oxidised black	78
Brass	Polished	4
	Polished, slightly tarnished	4.5
	After rolling	6
	Fresh rubbed with abrasive	20.5
Tin	Iron sheet, tinned	5.5
	Iron sheet, nickel plated, polished	4.5
	Iron sheet, nickel plated, dull	11
Zinc	Iron sheet, zinc plated, bright	24
	Iron sheet, zinc plated, grey	27.5
Iron	Sheet, newly treated with abrasive	24
	Cast, newly machined	43.5
	Sheet, stained	65
	Steel sheet, with skin due to rolling	66
	Steel sheet, with rough or brilliant oxide layer	81
	Cast, with smooth or rough cast skin	81

Some data on the absorption of radiant heat by metal surfaces, derived in part from Reference (2) are given in Table 2.

Some additional data on the absorptivities of steel, copper and aluminium for different wavelengths of thermal radiation are given in Table 1 of Section 3.2.2, Chapter 3.

References

(1) "Heat Transfer" M. Jakob, Vol.I p.126 (John Wiley, 1949)

(2) "The Calculation of Heat Transmission". M. Fishenden and O. A. Saunders, (H.M.S.O. 1932)

(3) Smith P. G., "Temperature Gradients in Painted and Unpainted Metals Subject to High Intensity Thermal Radiation Pulses". Joint Fire Research Organisation - S.R. Note No. 32/1957 (Confidential)

TABLE 2

ABSORPTION OF RADIANT HEAT BY METAL SURFACES

Metal	Percentage Absorption of Radiation from		
	Sun	Carbon arc Note (i)	Fireball (Note (ii)
Aluminium, superpurity electro-polished			14
Aluminium, pure, mechanically polished		11	
Duralumin	53		
Chromium plate	49		
Copper, mechanically polished			
Speculum metal, mechanically polished	39		
Gold, polished			
Iron, pure, polished	45		
Steel, polished	45		
Stainless steel			
Red Oxide of Iron	74		
Nickel, electrolytic	40	33	
Monel metal	43		
Platinum, pure	50		
Platinum, black	97		
Silver, polished	11	22	8
Tin		25	
Titanium		56	
Zinc, polished	46	48	

Note:- (i) These figures are probably too low as the metallic reflector to the arc removes near-ultra-violet radiation strongly absorbed by some polished metals, notably Al, Ag, Cr.

(ii) Preliminary calculation for a fireball at 6500°K.

4.3.2. Absorption by Painted Metal Surfaces

(a) Effect of pigment colour

The colour of the pigment will largely determine the degree of absorption, and values for a number of pigments are given in Table I for Solar Radiation (Reference (1))

Table 1

Absorption of Radiant Heat by Pigments

Colour	Material	Percent absorption of radiation from the sun
Black	Soot	99
Blue	Cobalt oxide	97
Green	Chromic oxide	73
Yellow	Lead chromate	30
Yellow	Lead oxide (PbO)	48
Red	Iron oxide	74
White	Alumina	16
White	Lead carbonate	12
White	Magnesia	14
White	Magnesium carbonate	15
White	Thoria	14
White	Zinc oxide	18

(b) Effect of the nature of pigment in white paint

A white pigment is a powder form of a transparent material which reflects a high total proportion of incident radiation by successive small reflections. As many paint media absorb radiation in the invisible portions of the spectrum, it follows that the reflective efficiency of a white paint depends to a considerable extent on the capacity of each pigment particle to reflect a high proportion of the radiation and thus limit the length of path of the radiation through the paint. The reflection coefficient of a pigment/medium interface is given by:-

$$\text{Reflection coefficient} = \frac{(\mu_p - \mu_m)^2}{(\mu_p + \mu_m)^2}$$

where μ_p is the refractive index of the pigment

and μ_m that of the medium.

The refractive indices of common white pigments are listed in Table 2 below.

Table 2

Pigment	Refractive Index
Silica	1.55
China clay	1.56
Whiting, calcium carbonare	1.58
Anhydrite, calcium sulphate	1.59
Mica	1.59
Talc	1.59
Blanc fixe, barium sulphate	1.63
Magnesium carbonate	1.64
White lead	2.0
Zinc oxide	2.0
Zinc sulphide	2.37
Titania, anatase	2.5
Titania, rutile	2.75

The refractive indices of paint media lie generally between 1.5 and 1.6. Slight increases occur during weathering.

In the commoner types of paint media, only those white pigments with refractive indices of two or more are efficient reflectors. Air voids greatly improve the reflectivity of a pigment, for at pigment/void interfaces $\mu_m = 1.0$. Whitewash and some distempers fall into this class.

The results of an investigation (Reference (2)) on paints are given in Table 3. The carbon arc absorption figures for the aluminium pigmented paints in this Table are probably too low, since the metallic reflector to the arc removes near ultra violet radiation. The following conclusions may be drawn from Table 3:-

(i) The absorptivity of finishes pigmented with rutile titania is about 25 to 30%. With multiple finishing coats, the figure can be reduced to near 20%, but at the expense of heat stability.

(ii) Nitro cellulose media tend to break down at relatively low temperatures, and to do so by rapid charring.

(iii) Stoving paints are more stable to heat than air-drying paints. The blistering of air-drying paints may be associated with solvent retention, especially where multiple coats have been applied. It is probable that a light stoving would increase the thermal stability of air-drying schemes.

American work on white paints (Reference (3)), has given the following results:

(i) Rutile titania was more reflective than anatase.

(ii) Silicone/alkyd media gave the greatest thermal stability.

(iii) Reflectivity increased markedly with increasing pigment/volume concentration.

(iv) Reflectivity increased with increase in the total thickness of the coating, 6 mils (0.006") being superior to 4 mils, which were, in turn, superior to 2 mils. There was no advantage in thicknesses greater than 6 mils.

(v) Reflectivity was increased by replacing part of the rutile titania by zinc oxide or china clay.

(vi) In schemes of total thickness of 2 mils, the colour of the primer had some effect, as whitening of the zinc chrome primer by addition of titania and china clay improved the reflectivity. It is not known whether the colour of the primer has any influence when it is covered by multiple finishing coats.

The reflectivities of rutile pigmented white cellulose and synthetic paint schemes (D.T.D.899A and D.T.D.827) for aircraft have been determined over the wavelength range 0.32 to 2.2 microns (Reference (4)). These schemes consist of varying weights of finish coats over a selection of filler type undercoats. The results indicate that the absorption of thermal energy occurs mainly in the rutile pigment. It is concluded that further improvement in reflectivity is unlikely whilst rutile is used as the sole pigment. However reflection of the energy in the ultra-violet (less than 0.4 micron) by a surface layer with no absorption of the energy in the visible and infra-red could increase the overall efficiency of the scheme to a nominal 95 per cent. The tests show that for these types of paint any increase in weight of the finish coat above 4 oz/yd^2 will not materially increase their reflective efficiency for radiation from a black body at $6000^\circ K$.

(c) Selection of paints

A single coat of paint applied by normal brushing or spraying technique weighs when dry, about 1 oz. per sq. yard, and has a thickness of about 1 mil. In calculating the temperature rise of painted metal, it should be assumed that the absorption figures quoted in Table 3 already include the effect of heat insulation due to the poor heat conductivity of the paint film.

The best paints for protection against heat flash consist of heat resistant media pigmented with titania and other white pigments which have absorptions of the order of 20 to 25%. It is hoped that current research will reduce this figure to about 17.5%. See also Reference (7).

It may be assumed that the absorption will rise rapidly as the paint scorches, reaching a figure of 60 to 90% when the paint chars.

Colours can be divided into two classes. For dark colours thermal stability is only of importance in so far as it is required to maintain the paint as protection against corrosion; charring will only raise the percentage of absorption of heat from a high value to a higher one. For colours of medium reflectance however, thermal stability of the paint is very important, for total heat absorption of a moderate absorber stable to high temperature could be less than that of a low absorber which breaks down at relatively low temperatures to become a high absorber. Some flame retardant treatments are mentioned in Chapter 6, Section 6.3 (iv).

(d) Skin temperature rise in aircraft

The skin temperature rise in an aircraft exposed to thermal radiation from a nuclear explosion is discussed in Reference (5). It is shown that in many situations aerodynamic cooling substantially reduces the temperature rise in thin skins of aircraft exposed in flight to thermal radiation from nuclear explosions. The maximum acceptable thermal dose, where this is determined by skin temperature rise, depends upon the time scale of the thermal input, and this upon the yield of the weapon involved.

In Reference (5) the problem is attacked by a finite difference analysis, and the maximum temperature rise and the time at which it occurs are shown to depend on a single non-dimensional parameter. The results are presented for a range of this parameter corresponding to the majority of practical situations.

The effects of non-uniform absorptivity of thermal radiation on the temperature rise in aircraft skin (e.g. under insignia) have been examined and are reported in Reference (6). Some recent tests of heating under load are reported in Reference (7).

References

(1) "The Caluclation of Heat Transmission". M. Fishenden and O. A. Saunders. (H.M.S.O. 1932).

(2) R.A.E. Farnborough (Chemistry Dept.) Unpublished Work.

(3) Vita-Var Corporation "Investigation of Protective Coatings to Decrease Vulnerability of Aircraft to Thermal Radiation". 1st, 2nd and 3rd quarterly reports (1954/55) (Confidential/Discreet) T.I.L. Nos. P.55101/2/3.

(4) R.A.E. Tech. Note Chem. 1323 (November, 1957) The Reflectivities of Rutile Pigmented White Paint Schemes for Aircraft over the Wavelengths 0.32 to 2.2 microns (Restricted)

(5) R.A.E. Tech. Note Mech.Eng. 251 (March, 1958) - Skin Temperature rise in an Aircraft exposed to Thermal Radiation (Confidential)

(6) R.A.E. Tech. Note Mech.Eng.268 (July, 1958) - The Effects of Non-Uniform Absorptivity of Thermal Radiation from Nuclear Explosions on the Temperature Rise in an Aircraft Skin. (Confidential)

(7) R.A.E. Test Note Structures 1519. July, 1958. Combined Transient Heating and Static Loading Test of a Valiant Aileron. (Confidential)

TABLE 3

ABSORPTION BY REPRESENTATIVE PAINT SCHEMES ON METAL SURFACES

Paint Scheme	Primer	Filler	Finish	Pigment in finish	Percent Absorption of radiation Carbon arc	Onset of deterioration in arc, °C
Nitrocellulose finish						
DTD.766A	Etch	None	Alhyd.N/C	Pol.Al.flake	39	200 S
DTD.722	Alkyd.X2	None	Alkyd N/C	Rut.TiO_2	35	150 Bl.C
DTD.722 Finish polish	Alkyd.X2	None	Alkyd.N/C	Rut.TiO_2	35	150 Bl.C
DTD.754	Etch	None	N/C	TiO_2+ SiO_2	30	230 S
Air Drying Alkyd						
Mat. DTD.314	Etch	None	Alkyd	TiO_2 + SiO_2	26	250 S
Glossy DTD.827	Etch	Alkyd + China clay	Alkyd	Special I.R. reflectors	54	200 Bl.S
"	"	"	"	Al, non-leafing	42	200 Bl.S
"	"	"	"	Al, leafing	40	200 Bl.
"	"	"	"	Al.polished	34	180 Bl.C
"	"	"	"	TiO_2	27	170 S
"	"	"	"	$TiO2$ + SiO_2	27	180 Bl.S
"	"	"	Alkyd - 3 coats	$TiO2$	22	150 Bl.S
Stoving Alkyd U/F						
DTD.235	Alkyd	None	Alkyd U/F	TiO_2 + SiO_2	30	250
Epoxy, cold catalysed						
DTD.900/4414	Epoxy	None	Epoxy	TiO_2	27	230 S
Epoxy, stoving						
-	Epoxy	None	Epoxy P/F	TiO_2	35	230 S
Silicone Air drying						
Mod. of DTD. 900/4381	None	None	Silicone	White	30	200 S
"	Etch	None	Silicone	White	35	200 S
Silicone stoving						
-	Silicone	None	Silicone	Pol.Al.flake	37	250
-	Silicone	None	Silicone	TiO_2	24	250
Butyl titanate						
-	Bu.tit.	None	Bu.tit.	Pol.Al.flake	24	250

Notes: Carbon arc. Radiation flux 4 cals/cm^2 per sec. giving a test panel temperature rise of rise of 13°C per sec.
N/C = Nitrocellulose
Pol.Al.flake = Polished aluminium flake pigment.
U/F = Ureaformaldehyde
P/F = Phenol formaldehyde
Etch = Etch Primer, DTD.868
I.R. = Infra-red
S. = Scorching to a yellow colour
Bl. = Blistering
C. = Charring

4.4. The Mechanical Properties of Metals Heated for Short Periods

4.4.1. Introduction

In general the strength of metal falls with the rise of temperature. Over a range of 200°C, however, the fall may be modified and in the case of lowly alloyed steels even reversed, by an effect known as strain ageing or strain hardening, attributed to an incipient precipitation of impurity atoms within the crystal lattice impeding further slip. The temperature range over which this phenomenon occurs in steel is 200-400°C. Heat treatable alloys which rely for their strength on the formation or incipient precipitation of a metastable phase may lose both strength at temperature and residual room temperature strength rapidly when temperatures are reached at which local or metallurgical changes of structure occur quickly. With heat treatable aluminium alloys, these permanent changes occur at 200-250°C, depending on the type of alloy. The elastic stiffness (Youngs Modulus E) which is a property of each individual metal, and is substantially independent of the presence of alloying elements, falls steadily with rise of temperature. Recovery at room temperature is normally complete, if no changes of state have occurred.

The extent of thermal damage will depend both on the temperature and the time for which it is maintained. Very few results are available for brief heating, but an estimate of the effects may be based upon data for extended heat treatment. In most cases available data refer to room temperature measurements following heat treatment, but in some cases actual properties at the elevated temperatures are given. In many cases of military interest, it will be the actual time history of the strength of the material during heating that will be important. There are no such data available at present.

Sections 4.4.2. - 4.4.6. present typical data for the following properties:

(i) Tensile strength at temperature. In the case of unstable alloys which undergo permanent metallurgical changes at relatively low temperatures, the data are taken from short time tensile tests where these are available.

(ii) Young's Modulus at temperature.

(iii) Short time creep data at temperature. These are taken from U.S. Air Force Project Rand. (Reference 1).

(iv) Recovery properties at room temperature of unstable alloys.

A useful collection of papers on the behaviour of metals at elevated temperatures is presented in Reference (2).

In illustration of an extreme case of the problem, Figures 1A and 1B (taken from Reference (3)) give the material loss from spheres of various materials due to ablation or scaling off of the surface material from contact with or envelopment by the fireball. Data for three types of 10-inch diameter spheres are shown; namely, solid steel, solid aluminium, and solid aluminium with small cylindrical wells filled with ceramic inserts. The one curve in Figure 1A represents all three types.

References:

(1) Project Rand. Report R-147, U.S. Air Force, June, 1949.
Ministry of Supply Gas Turbine Collaboration Committee
R.C.301, 16831. (Restricted Discreet).

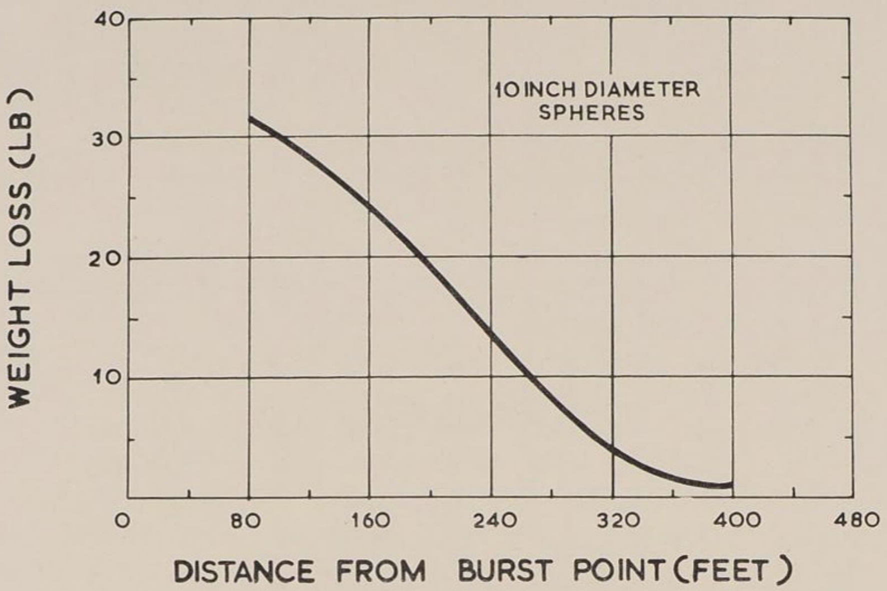
(2) Behaviour of Metals at Elevated Temperatures
- Institute of Metallurgists. (Iliffe & Sons, 1957)

(3) Capabilities of Atomic Weapons (1957)
U.S. Dept. of the Army, TM 23-200 (Confidential)

(4) High Temperature Effects in Aircraft Structures. N. J. Hoff
(Pergamon Press Ltd. 1958)

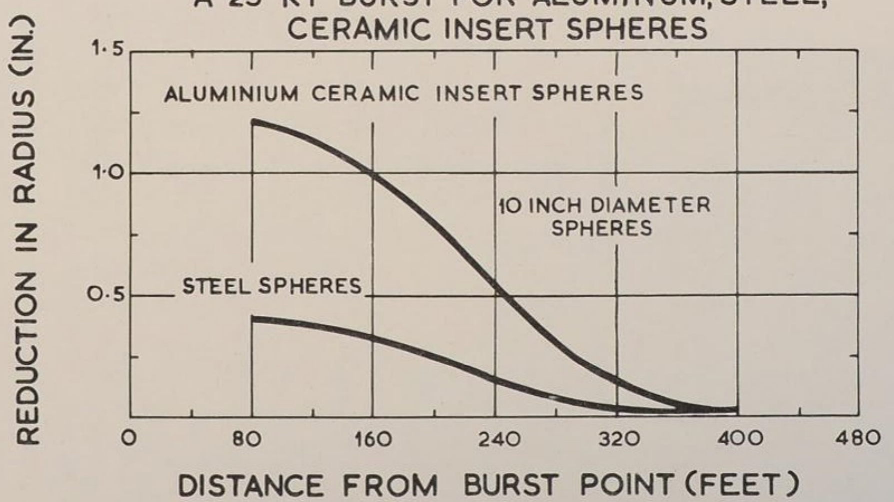
A.

WEIGHT LOSS WITH DISTANCE FROM A 23 KT BURST FOR ALUMINUM, STEEL, CERAMIC INSERT SPHERES



B.

REDUCTION OF SPHERE RADIUS WITH DISTANCE FROM A 23 KT BURST FOR ALUMINUM, STEEL, CERAMIC INSERT SPHERES



ABLATION OF METAL SPHERES BY THERMAL RADIATION

4.4.2. Mild Steel

Tensile strength at temperature - The variation of ultimate tensile strength with temperature of a range of plain carbon steels is shown in Figure 1 (Reference (1)). Up to 150°C the drop in strength is negligible. The strength increases up to about 300°C, and then falls rapidly, passing the room temperature value at about 400°C. In contrast to the ultimate tensile strength, the 0.1% proof stress remains unchanged up to 200°C and then falls appreciably, as indicated by Figure 2, taken from Reference (2).

The changes in strength with temperature are substantially independent of period at temperature up to 400°C.

Young's Modulus at temperature - The fall in E with rising temperature is shown in Figure 3 (Reference (2)).

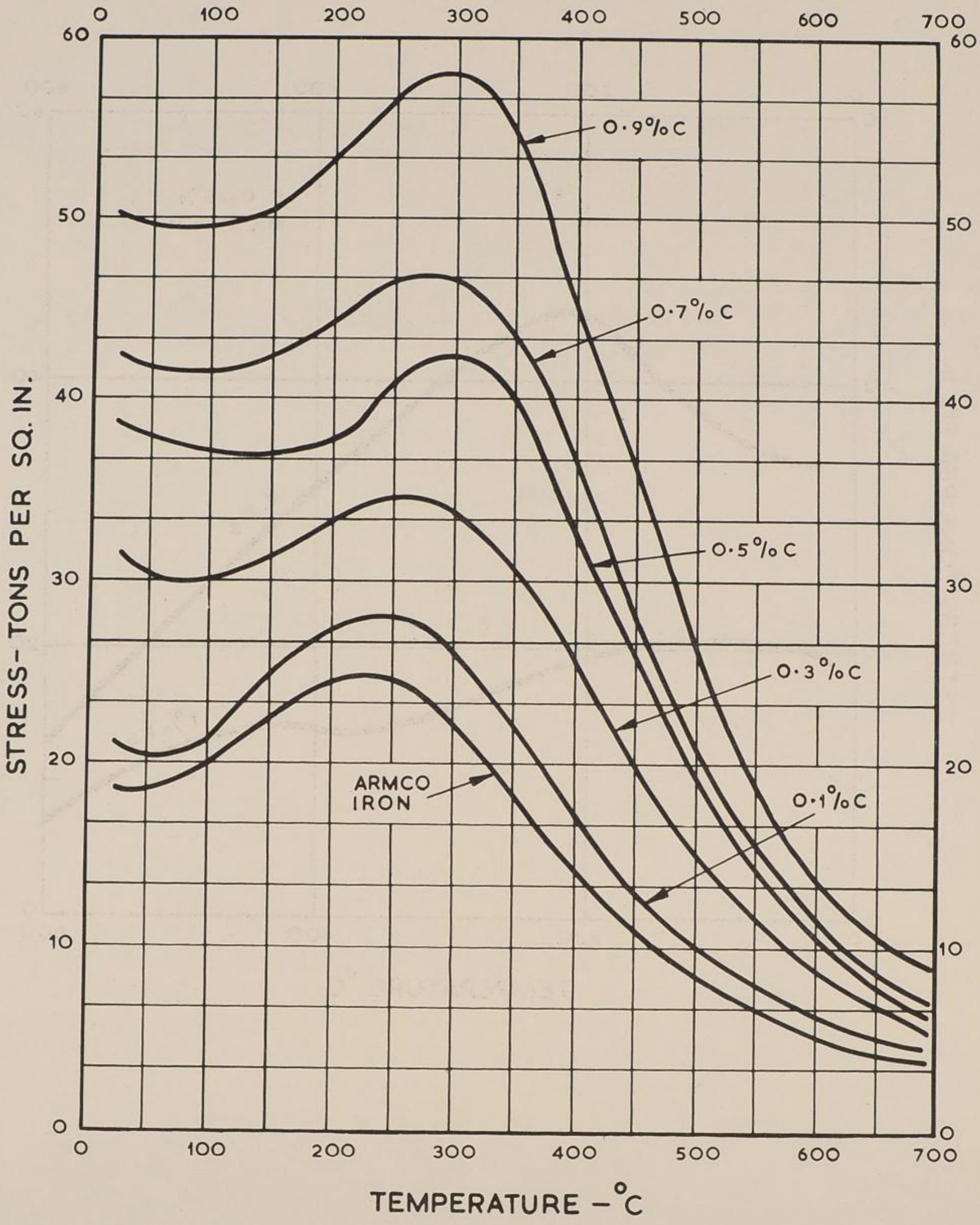
Short time creep properties - No data known.

Recovery strength - The room temperature strength is unaffected by heating, even for prolonged periods, at up to 400°C.

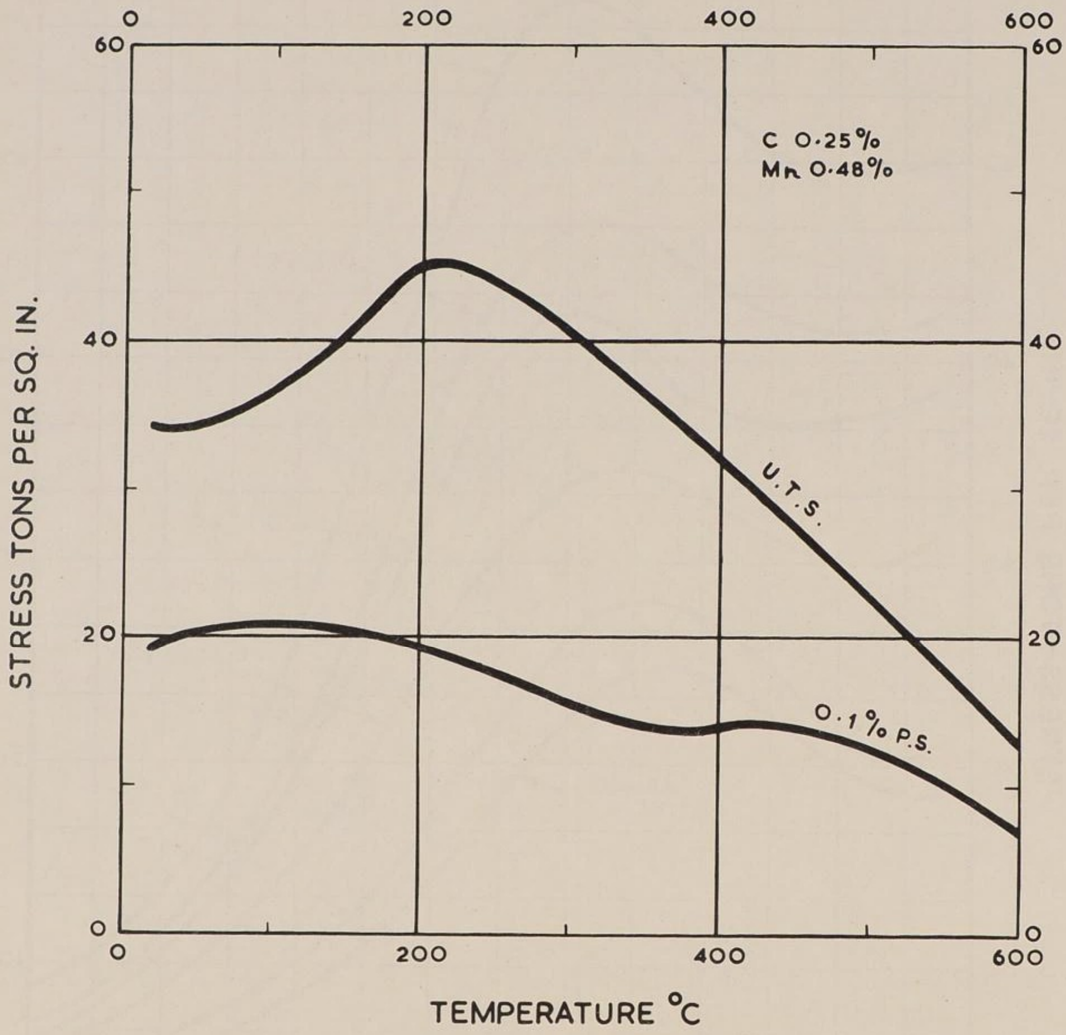
References

(1) Metals, Vol. 1. Carpenter and Robinson, page 177.

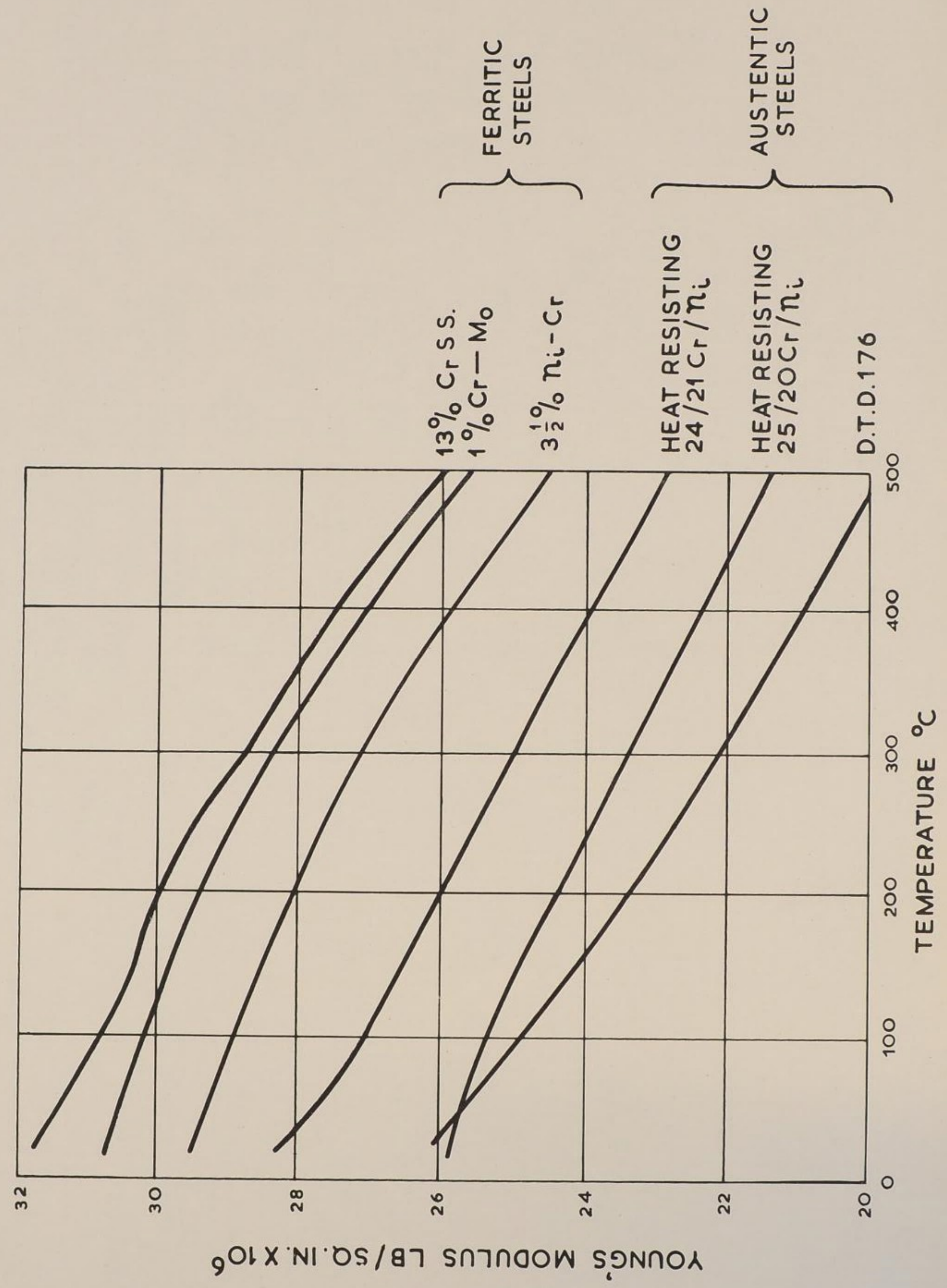
(2) R.A.E. Technical Note Met. 199, June, 1954. "The Effect of Heating Steels to Moderately Elevated Temperatures".



VARIATION OF ULTIMATE TENSILE STRENGTH WITH TEMPERATURE FOR A RANGE OF CARBON STEELS



VARIATION OF STRENGTH OF MILD STEEL
WITH TEMPERATURE



VARIATION OF YOUNG'S MODULUS WITH TEMPERATURE

4.4.3. Carbon and Low Alloy Steels

Tensile strength at temperature - The percentage fall in proof stress and ultimate tensile strength of a range of structural steels with rise of temperature is shown in Table 1. The results may be summarised as follows:-

	150°C	250°C	350°C
Proof stress	Drop of 10%	Drop of 15 to 20%	Drop of 20 to 25%
Ultimate tensile strength	Drop of 4 to 8%	Drop of 0 to 5%	Drop of 10 to 15%

EN110 nickel chrome molybdenum steel, however, retains its properties almost unchanged up to 300°C.

Young's modulus at temperature - Typical data for ferritic steels are shown in Figure 3, Section 4.4.2. Detailed figures for many steels are given in Reference (1).

Short time creep properties - The only data available are for SAE.4130 chrome molybdenum steel sheet at 650°C. These are summarised in Table 2.

Recovery strength - Periods of a few minutes at temperatures up to 400°C are not expected to have any permanent effect on tensile properties or to produce temper brittleness, except perhaps in the case of ultra high tensile steels tempered at 200 to 250°C. No data are available on the effect of short period heating on these steels, but it is thought that some loss of strength might occur at 300°C and more.

References

(1) R.A.E. Technical Note Met. 199, June, 1954. "The Effect of Heating Steels to Moderately Elevated Temperatures."

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TABLE 1

Tensile properties of carbon and low alloy structural steels at elevated temperatures

(The properties are substantially independent of period at temperature)

Steel	Form	Heat Treatment	Room temp. properties tons/sq.in. FS	UTS	Percentage drop in properties at temperature: 100°C FS	100°C UTS	150°C FS	150°C UTS	200°C FS	200°C UTS	250°C FS	250°C UTS	300°C FS	300°C UTS	350°C FS	350°C UTS	400°C FS	400°C UTS
1. Carbon manganese, weldalile, C 0.23%, Mn 1.7%	Bar		26 (0.2%)	39	4 (0.2)	+2	9 (0.2)	+5	14 (0.2)	+8	18 (0.2)	+12	21 (0.2)	+10	22 (0.2)	+2	22 (0.2)	10
2. Manganese molybdenum, C0.43% Mn 1.8%, Mo 0.21%	Bar	WQ 815°C T 540°C	55 (YP)	61	7 (YP)	4	9 (YP)	5	11 (YP)	4	14 (YP)	4	18 (YP)	4	24 (YP)	8	32 (YP)	14
3. 1% chrome molybdenum, C0.38% Cr 1.0%, Mo 0.20%	Bar	OQ 845°C T 625°C	57 (YP)	64	9 (YP)	3	10 (YP)	4	11 (YP)	4	10 (YP)	5	14 (YP)	5	19 (YP)	9	26 (YP)	16
4. 1% chrome molybdenum EN 20	Bar	As En 20	61	66	-	-	-	-	19	2	21	+1	24	1	29	8	32	15
5. Nickel chrome molybdenum S.11 (EN.23)	Bar	As En 23	50	60	8	7	10	8	14	9	14	5	16	1	22	10		
6. Nickel chrome molybdenum EN.24	Bar	As En 24	65	72	8	5	11	7	16	8	14	6	20	9	24	13		
7. Nickel chrome molybdenum EN.25	Bar	As En 25	70	77	7	5	11	7	18	8	18	6	20	9	24	13		
8. Nickel chrome molybdenum EN.110	Bar	As En 26	56	72	+3	4	1	5	3	7	1	5	6	8	15	15		
9. Chrome molybdenum SAE.4130	Sheet	OQ 900°C T 370°C	62	64					40	23							48	28 (at 427°C)

Data for steels 1 to 8 from ref. 3, for steel 9 from ref. 1
YP - Yield point, i.e. limit of proportionality.
FS - 0.1% proof stress unless otherwise stated
UTS - Ultimate tensile strength.

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TABLE 2

Short time creep of steels

Metal	Condition	Room temp. strength tons/sq.in.		Heating rate °C per sec.	Temp. of test °C	Thermal expansion %	Stress, tons/sq.in to give 2% total extension			Stress to give 4% total extension		
		0.2% P.S.	U.T.S.				6 secs.	12 secs.	30 secs.	6 secs.	12 secs.	30 secs.
Steel Chromium molybdenum SAE 4130 0.30C 0.9Cr 0.2Mo	Annealed 1 hr. at 900°C			52-66	650	1.12	13.8	12.5	10.0	14.0	13.5	12.7
Chromium molybdenum SAE 4130 0.30C 0.9Cr 0.2Mo	OQ from 900°C T 1 hr. 370°C	63.5	64.5	52-66	650	1.12	>14	12.7				>15

4.4.4. Heat Resisting Steels

These are of two types, the austenitic (high chromium and high nickel) and the ferritic (high chromium with low nickel, and high chromium with high nickel plus other elements which destroy the austenite stability imparted by nickel).

Tensile strength at temperature - Some typical data are given in Table 1. These steels retain their properties well, and are being actively developed for high speed aircraft structures.

Young's modulus at temperature - Typical data are shown in Figure 3, Section 4.4.2. A steady drop in E occurs, but the values for ferritic steels are appreciably higher at any temperature than those of austenitic steels.

Short time creep data - Data for two types of 18/8 steel are given in Table 2. Reference (1), from which the data where taken, includes similar information for a number of high temperature alloys, viz. 25 Cr - 20 Ni - 2 Si steel, inconels, hastelloys and stellite.

Recovery properties after heating - Recovery is normally complete for short periods of heating up to 500°C.

References

(1) Project Rand, Report R-147, U.S. Air Force, June, 1949.
Ministry of Supply Gas Turbine Collaboration Committee RC.301.
16831. (Restricted/Discreet)

UNCLASSIFIED

TABLE 1

Tensile properties of heat resistant structural steels at elevated temperatures

(The properties are substantially independent of period at temperature).

Steel	Form	Heat Treatment	Room temp. properties tons/sq.in.		Percentage drop in properties at temperature													
					100°C		150°C		200°C		250°C		300°C		350°C		400°C	
			PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS
1. Stainless iron, C 0.1% max.,CR 13.5	Bar	-	23	29	9	10	13	15	13	18	13	18	9	18	13	20	17	23
2. Stainless steel B.S. S62 C 0.25%,Cr.13.5	Bar	-	30	45	10	6	13	11	13	13	17	15	17	18	20	20	23	22
3. Stainless steel DTD.166 Austenitic	Sheet	Cold rolled	50	57	18	10	22	12	24	14	26	16	26	16	28	16	28	17
4. Stainless steel DTD.176 Austenitic	Bar	Annealed	12	42	25	19	25	24	25	26	25	29	25	29	25	29	25	29
5. Stainless steel Rex 448 Cr 11% with Mo, V, Nb	Sheet	-	58	77	3	8	9	10	17	12	17	12	17	13	22	18		
ditto	Bar	Heat treated	55	70	5	6	9	9	13	11	13	13	13	17	15	20	16	26

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TABLE 2

Short time creep of steels

Metal	Condition	Room temp. strength tons/sq.in.		Heating rate °C per sec.	Temp. of test °C	Thermal expansion %	Stress, tons/sq.in. to give 2% total extension			Stress to give 4% total extension		
		0.2% P.S.	U.T.S.				6 secs.	12 secs.	30 secs.	6 secs.	12 secs.	30 secs.
Stainless steel, 18/8, 0.02C	Annealed 1100°C	14.0	36.0	52	815	1.63	9.0	4.9	3.6	9.8	8.0	6.7
Stainless steel Type 347, 18/8 + Cb.	Half hard	65.6	67.5	52	650	1.28		31.6	19.2	35.7	34.8	33.5

4.4.5. Aluminium Alloys

The stronger aluminium alloys rely for their strength on a solution heat treatment followed by an incipient precipitation induced by ageing at temperatures ranging from room temperature to 200°C depending on the alloy. Strength falls with rise of temperature, and when the ageing temperature has been passed, the fall in strength due to discrete precipitation is rapid and, in part, permanent. These gross and permanent changes occur rapidly at temperatures from 200°C and are within the range which might be reached by unprotected structures subject to heat flash. The temperatures are thus much lower than those at which somewhat analogous metallurgical changes occur in steels. Some aluminium alloys become susceptible to corrosion or stress corrosion at temperatures much lower than 200°C, but no data are available on whether this type of change occurs during very short periods of heating.

Tensile strength at temperature - Much information is available on the properties of cast, forged and extruded alloys at temperatures up to the levels at which reversible changes occur (References (1), (2) and (3)). Few data exist however, for the critical temperatures, and few short time tensile tests have been made. Table 1 lists the properties of some typical types of alloy.

Young's modulus at temperature - The Young's Modulus drops steadily with temperature. It is substantially independent of reversible or irreversible changes in other tensile properties.

Short time creep data - Available data are confined to 2S commercially pure aluminium sheet, and 75S alloy sheet, equivalent to DTD.687. These are summarised in Table 2.

Recovery properties after heating - The room temperature tensile properties of two alloys have been determined after short periods of heating (Reference (1)). Results are summarised in Table 3.

No data have been found for other alloys. Table 4 indicates the dangerous temperatures for a range of alloys; for L71 and L73 and for DTD.687, the figures are taken from Table 3, and for the remaining alloys estimates have been made by analogy.

Some recent combined transient heating and static loading tests on a Valiant aileron are reported in Reference (4).

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TABLE 1

Strength of representative aluminium alloys at elevated temperatures.

Alloy	Strength at room temp. tons/sq.in.		Percentage drop in properties at temperature											
			150°C 1 hr.		150°C 10 hrs.		200°C 1 hr.		200°C 10 hrs.		250°C 1 hr.		250°C 10 hrs.	
	0.1% PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS
DTD.364 bar (Al Cu type aged 200°C)	27.5	33.0	7	15	7	12	18	30	24	30	47	51	64	67
DTD.683 bar (Al Zn Mg type, aged 130°C)	28.0	34.0	16	24	16	27	41	32	50	57	68	71	77	78
75 ST sheet (Al Zn Mg type)	31.6	36.4					63*	56*						
L.42 (RR59) bar (aged at 200°C)	19.5	29.5	5	14	5	14	10	22	5	24	20	37	28	44

*"Short time test" at 205°C.

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TABLE 2

Short time creep data on aluminium alloys

Metal	Room temp. strength tons/sq. in.		Temp. of test	Thermal expansion %	Stress, tons/sq. in. to give 2% total extension			Stress to give 3% total extension			Stress to give 4% total extension		
	0.1% P.S.	U.T.S.			6 secs.	12 secs.	30 secs.	6 secs.	12 secs.	30 secs.	6 secs.	12 secs.	30 secs
Aluminium sheet 2S commercially pure	8.0	8.3	149°C	0.32	7.4	7.2	6.7	7.5	7.3	6.9	-	-	-
			205°C	0.44	-	6.2	4.9	-	6.3	5.3	-	-	5.4
			315°C	0.83	-	2.5	1.6	-	2.6	2.1	-	-	2.4
Aluminium alloy sheet 75 ST, heat treated and aged, equivalent to DTD.687	31.7	36.5	149°C	0.30	29.5	28.4	27.3	30.0	28.8	27.6	-	29.0	28.0
			205°C	0.43	-	22.0	21.2	-	22.0	21.6	-	22.0	21.6
			315°C	0.83	-	5.8	5.6	-	5.8	5.6	-	5.8	5.6

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TABLE 3

Recovery Properties of Aluminium Alloys After Heating.

Alloy	Room temp. properties tons/sq.in.		Period at temperature secs.	Percentage drop in room temp. properties after heating									
				180°C		200°C		250°C		300°C		340°C	
	PS	UTS		PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS
Aluminium alloy sheet DTD.546	25.0	30.0	5	0	0	0	0	3	2	18	11	33	17
			10	0	0	0	0	4	2	22	13	40	21
			30	0	0	0	0	6	4	28	18	49	28
Aluminium alloy sheet DTD.687	30.0	34.0	5	0	0	0	0	18	15	28	17		
			10			3	5	20	16	38	23		
			30			12	10	25	20	48	30		

TABLE 4

Alloy	Ageing Temperature	Damage Temperature
NS5, 3.5% Mg type	-	350° by annealing
NS6, 5% Mg type	-	Ditto, but may become susceptible to stress corrosion
H10, Mg Si type	180°C	250°C
H14, Cu type	Room temperature	250°C but may become more susceptible to corrosion
H15, L70, L72 Cu Si Fe type	Room temperature	250°C. At lower temperatures the material will age to L71, L73
H15, L71, L73 Cu Si Fe type	Up to 205°C	250°C
DTD.687 Zn Mg Cu type	130°C	200°C

References

(1) R.A.E. Technical Note Met. 197, May, 1954. The tensile Properties of D.T.D.546 & D.T.D. 687 after heating at elevated temperatures."

(2) Bristol Aeroplane Company. "Properties of Wrought and Cast Aluminium and Magnesium Alloys at Atmospheric and Elevated Temperatures", by P.H. Frith. To be issued in parts in the S & T. Memo. Series.

(3) Handley Page, Ltd., Stress Note 52, May, 1955. To be issued in the S.& T. Memo. Series.

(4) R.A.E. Test Note Structures 1519. July 1958. Combined Transient Heating and Static Loading Test of a Valiant Aileron. (Confidential)

4.4.6. Magnesium Alloys

The structural magnesium alloys are of two types, the magnesium aluminium type and the magnesium zinc zirconium type. The former type is not strengthened by solution heat treatment if the aluminium content is below about 9%, as is the case for wrought alloys; thus, although heating may induce precipitation, there is little permanent effect on properties until a temperature of about 200°C is reached, at which grain growth and permanent weakening begin. The magnesium zinc zirconium alloys are not susceptible to a solution heat treatment; grain growth occurs at above 250°C, but is relatively slow.

Tensile strength at temperature - Some figures for the strength of typical wrought magnesium alloys at elevated temperatures are given in Table 1.

The figures show that the fall in properties is very marked. Falls of this order are not found in the cast alloys containing zirconium and rare earths; attempts are being made to develop wrought alloys of this type.

Short time creep data - Some data on two alloys are summarised in Table 2. Data for ZW1 extruded bar, in which the stresses required to produce strains of from 0.05% to 0.5% at 150°C, 180°C and 200°C, have also been published (Reference (1)).

Recovery properties after heating - No permanent effect on room temperature properties is likely to result from heating to temperatures of up to 200°C. Above this temperature, permanent softening will occur.

The only data found are some R.A.E. results (Reference (2)), on the effect of 10 second periods of heating on ZW3 (DTD.626) sheet. At 250°C, no effect was found, and at 320°C a drop of 4% in the 0.1% proof stress occurred.

References

(1) Magnesium Elektron, Ltd., Technical Bulletin No.1, July, 1953.

(2) R.A.E. Technical Memorandum Met. 600, October, 1955.

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TABLE I

Strength of Representative Magnesium Alloys at Elevated Temperatures

Alloy	Room temp. props. tons/sq.in.		Percentage drop in Properties at Temperature									
			50°C		100°C		150°C		200°C		250°C	
	PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS	PS	UTS
AZ31 "Wrought" (PS values are 0.2%)	12.8	17.0	12	4	30	19	49	38	67	55	78	69
AZ31, FS1A, sheet	10.2	17.2							73 at 205°C	69		
AZM bar, D.T.D.259		18.8		8		19		31		51		73
ZW3 sheet, D.T.D.626		18		11		33		51		67		78
ZW3 bar, D.T.D.622A	16.4	21.0	19	20	41	43	62	53	83	60	95	68
ME-10, sheet (Mn Ce alloy sq. to AM537) Ann.	10.2	15.0							46 at 205°C	51		
ME-10, h.t. 1 hr. 482°C aged 16 hr. 205°C	7.3	12.5										

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TABLE 2

Short time creep of magnesium alloys

Metal	Room temp. strength tons/sq. in.		Temp. of test	Thermal expansion %	Stress, tons sq. in. to give 2% total extension			Stress to give 3% total extension			Stress to give 4% total extension		
	0.1% P.S.	U.T.S.			6 secs.	12 secs.	30 secs.	6 secs.	12 secs.	30 secs.	6 secs.	12 secs.	30 secs.
Magnesium alloy sheet FS1A, equivalent to AZ31	11.0	17.2	149°C 205°C 315°C	0.38 0.53 0.92	9.8 5.8 2.7	9.8 5.5 2.0	6.3 5.0 1.0	9.8 - -	9.8 5.7 2.2	7.4 5.3 1.7	- - -	9.8 - -	7.8 5.4 2.1
Magnesium alloy sheet ME10, (Mn Ce alloy) Annealed	10.2	15.0	149°C 205°C	0.31 0.43	9.2 7.3	8.8 7.2	8.3 6.7	9.3 7.3	8.9 7.2	8.6 7.0	9.4 7.3	9.1 7.3	8.7 7.1
Ditto, heat treated as Table 1	7.3	12.5	315°C	0.78	-	3.6	3.1	-	-	3.4	-	-	3.6

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November, 1958.

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4.5. Thermal Damage to Miscellaneous Service Equipment

4.5.1. Chemical Warfare Equipment

(a) Service respirators - The exposure of obsolescent respirators G.S. during Operation Totem (Reference (1)), showed that there was no increased hazard due to ignition of the rubber mask following a nuclear explosion, but that on the contrary, the mask gave a considerable measure of protection against facial burns. (See Section 4.2.1 for details.)

A further exposure trial during Operation Buffalo (Reference (2)) was intended to provide information on the new Service respirator (which is now in the final stages of Service trials and development), particularly with regard to the pneumatic periphery. It was also desired to obtain information on respirators within haversacks. Twelve respirators (Type D46/36) which were exposed on dummy heads to thermal doses from 2-96 cals/cm^2 behaved similarly to the respirators exposed at Operation Totem. They remained undamaged up to 8 cals/cm^2, and the majority would probably have been serviceable up to 12 cals/cm^2, in spite of surface melting of the external surface of the rubber. The internal surfaces, including the air bag, were not affected even at 32 cals/cm^2, and it is clear that external heat damage to the mask and head harness is the controlling factor from the respirator serviceability aspect. The new respirator is therefore no more vulnerable than the old respirator G.S., and owing to the pneumatic fitting would certainly give greater protection against heat, but this advantage would be offset by the increased exposure of the eye region through larger eyepieces.

Respirators in haversacks were unaffected up to 32 cals/cm^2, and at higher levels impact with surrounding objects as a result of blast is likely to be the factor controlling serviceability. The haversacks themselves showed slight discolouration at 6 cals/cm^2, but remained intact, although severely scorched at 32 cals/cm^2. At higher levels they were torn apart by blast, but were still not seriously affected by the heat.

It appears reasonable to conclude that worn respirators will remain serviceable under conditions in which the incidence of lethality for exposed men is high. (Cf. Chapter 7)

(b) Kits, Capour Detector - Of the six K.V.Ds exposed at Operation Buffalo, four were almost completely destroyed by burning, and were not returned to the U.K. for examination. Of the two returned, no particulars of the thermal dose received were known in one case, and the other kit was at a site which received 48 cals/cm^2. Of the two kits examined, the canvas carrying cases were badly scorched, the cotton seam had given way, and the strengthening plastic sheet had come out. Tests were carried out in the normal way for mustard gas and nerve gas vapour, with results normal for the K.V.D., showing in particular that the tablets had not been adversely affected by the heat.

(c) Detector Powder - Six tins of detector powder were exposed to various thermal doses with the following results:-

8-12 cals/cm^2 - slightly scorched
16-24 cals/cm^2 - scorched and dented
32-48 cals/cm^2 - blackened and badly dented at one side.

In all cases the powder had not been affected in any way and responded to tests for liquid contamination.

(d) Detector Paper - Boxes of detector paper pads were exposed at sites receiving heat doses of 8, 12, 16, 24 and 32 cals/cm^2. Though scorching and blackening had occurred on one side of the boxes, this was entirely superficial and had not affected the paper in any way. Response to liquid contamination was normal.

Some single sheets of paper were also exposed to thermal doses ranging from 2-128 cals/cm^2. Below 6 cals/cm^2 there was no visible effect; above this dose scorching and charring occurred progressively, until, at the highest doses the middle of the sheet was burnt out. In all cases reactions were obtained in tests for liquid contamination, though in some cases where the paper had been scorched badly, very fine contaminating drops might not be seen, particularly the yellow colour of the nerve gas test.

References

(1) A.W.R.E. Report No. T77/54, Operation Totem.
"Effects on Respirators Anti-Gas (Confidential)

(2) A.W.R.E. Report No. T28/58. Operation Buffalo,
Target Response Tests. Materials Group.
Part 9(a): Effects on Chemical Warfare Equipment (Confidential)

4.5.2. Aircraft Windscreens (Reference (1))

Three types of panels representing current practice in the construction of bullet-proof windscreens were exposed at a number of sites at Operation Buffalo to a 15-20 KT nuclear explosion. The types of panel chosen were:-

(a) bullet-proof panels 12" x 12" x 1.5", incorporating an annealed glass;

(b) front panels from a Vampire windscreen, length approximately 22 ins, width tapering from 12 ins. to 8 ins, thickness 2.2 ins.

(c) Hunter windscreen, length approximately 24 ins, width tapering from 13 ins. to 4 ins, thickness 1.5 ins.

The panels were exposed vertically in the metal frames, slightly above ground level, at sites which received thermal doses of 12, 16, 24, 32, 48 and 64 cals/cm^2 respectively.

Panels at the two nearest sites to ground zero were torn from their frames and thrown several yards, sustaining some impact damage. Frames at the remaining sites were buckled, but the panels were still in place. The exposure face was in all cases pitted by sand blasting, the degree of damage becoming progressively less with increased distance from ground zero. The light transmission had of course, been affected by this pitting, but it is doubtful if pitting would have occurred had the panels been exposed at the height and angle equivalent to their normal position in an aircraft. In no case had the Vinal interlayer been visibly affected by the thermal radiation. Detailed results are given in Table I.

TABLE I - Damage to Aircraft Windscreens at Operation Buffalo

Feet From GZ	Total Heat Dose cals/cm^2	Annealed Panel	Vampire Windscreen	Hunter Windscreen
1840	64	All glass layers cracked 1st layer 6 in. crack 2nd layer 3 in. crack 3rd layer 7 in. crack 4th layer 4 cracks max. length 6 in. Both exposed glass surfaces pitted	Broken in two. Rear face missing. All remaining glass layers heavily cracked. Some separation of inter-layer along cracks. Front face heavily pitted	Front and rear glass layers cracked. Front layer 5 cracks across width. Back layer three 1 in. cracks Front Face very heavily pitted
2070	48	Back two layers cracked. Rear 0.2 in layer three cracks maximum length 4 in. Rear 0.5 in. layer 4 in. crack. Front face pitted.	Rear face missing. Otherwise no cracks. Front face heavily pitted.	Front layer cracked, (7 in. length). Front face pitted.
2560	32	Back layer cracked (2 in. length). Front face pitted.	Rear face heavily cracked. Front face heavily pitted.	No cracks. Front face pitted.
2950	24	No cracks. Front face slightly pitted.	No cracks. Front face slightly pitted.	No cracks. Front face very slightly pitted.
3570	16	No cracks Front face slightly pitted	No cracks Front face slightly pitted	Back layer cracked (two 2 in. cracks) Front face very slightly pitted.
4050	12	No cracks Front face very slightly pitted.	No cracks. Front face very slightly pitted.	Front and back layers cracked at edge. Front layer 5 in. crack Back layer 1 in. crack No pitting.

It is concluded in Reference (1) that all three types of panel behaved very well. The impact damage (i.e. cracking and pitting) would probably not have occurred had the panels been exposed as part of aircraft, and in any case were at damage levels at which the aircraft themselves would have been rendered non-operational. The Vinal interlayer, although soon damaged by sustained exposure to comparatively low temperatures, was not affected even by the highest thermal flux to which it was subjected.

References

(1) A.W.R.E. Report No. T.28/58. Operation Buffalo Target Response Tests, Materials Group.
Part 9(c): Effects on Aircraft Windscreens.
(Confidential)

CHAPTER 5 - THERMAL DAMAGE TO VEGETATION

5.1. Types and Conditions of Vegetation

Under certain conditions, the employment of an air burst weapon over a forest or wild-land area, may cause fires. During the fire season*, even when the burning potential is low, fires may spread. Wild-land fuels are generally a mixture of thin and heavy fuel components. Thin fuels are typified by surface litter and grassland; heavy fuels by fallen branches. The thinnest fuel present determines the ignition energy for the mixture. Heavy fuels do not ignite and continue to burn by themselves, but thin fuels may serve as the source of a pilot flame and may spread fire after the end of the radiant pulse. The following information on types and conditions of vegetation has been obtained from Reference (1).

During the fire season, ignitions may be expected in kindling fuels where the total thermal energies exceed 2 - 3 cals/sq.cm. for a 1 KT weapon. As the yield increases, the minimum ignition energies increase as $W^{\frac{1}{8}}$, i.e. 8-10 cals/sq.cm. would be required from a 30 MT weapon to ignite the thinnest wild-land fuels.

It is estimated that very few ignitions will occur within a forest in which the tree canopy shades more than 20% of the ground surface. Green leaves on tree crowns smoke and char, but do not normally sustain ignition.

Table 1 summarises the conditions which exist in forest and heath areas etc., during the fire season; the latter varies in different locations according to temperature and rainfall.

* For definition see Table 1.

TABLE I

The Condition of Wild land Fuels During Fire Season

Fuel Type	Description	Amount and Density of fuel to constitute a fire hazard	Condition During Fire Season
Grass or heath	Grassland, dry bracken, ferns, seasonal plants	Uniform grass cover ½ ton or more per acre	Vegetation nearly dry or dead
Evergreen bush	Perennial evergreen shrubs and brush	75% or more area covered	15-25% by weight of leaves and twigs dead
Deciduous forest	Forest predominantly of broad-leaf trees, leaves of which die and fall each year	Ground covered with more or less continuous layer of dead leaves	Leaves off trees. Ground vegetation dead or non-existent
Coniferous forest	Forests of evengreen pines - needle bearing trees	Ground covered with a more or less continuous layer of dead needles and twigs	Needles and twigs dry enough to break easily when bent. Grass and other vegetation present dry or dead.

The majority of thin wild-land fuels which serve as kindling material are divided, in Table 2, into four classes corresponding to different minimum ignition energy levels. Ignition energies increase as fuel moisture content increases. Since ignition generally occurs on those surfaces most exposed to the atmosphere, ignition energies are a function of relative humidity, as shown in Figure 1.

TABLE 2

Classes of Thin Wildland Kindling Fuels (in order of flammability)

Class	Description
I.	Broadleaf and coniferous litter; mixture of fine grass, broken leaves and thin translucent broadleaf leaves.
II.	Hardwood and soft wood in various stages of fungoid decay.
III.	Dried or dead grass.
IV.	Conifer needles and thick, nearly opaque broadleaf leaves.

Fires may be blown out by blast depending on the time interval between ignition and arrival of the shock. Blowout is not expected in regions below 5 p.s.i. for fully exposed fuels. If the fuel is in a hole or pocket, the chance of blowout is materially decreased. When fires are not blown out, they generally increase in intensity owing to the action of the blast wind.

The principal factors, apart from the fuels present, that influence the burning potential of forest or wild-land areas, are the nature of the terrain, the wind speed close to the ground, the relative humidity, and the precipitation history. An approximate guide for evaluating the effects of weather or burning potential is given in Table 3. Fuels seldom burn vigorously, regardless of wind conditions when the fuel moisture is greater than 16 percent. This corresponds to an equilibrium moisture content for 80 percent relative humidity. About a quarter of an inch of rain renders fuels temporarily non-inflammable, and may extinguish going fires in thin fuels. The time required to restore the burning potential may vary from hours to days depending on local weather conditions. Surface fuels in the interior of forests are exposed to reduced wind velocities and generally have high fuel moistures due to shading by the canopy.

Table 3 - Burning Potential for Light Wildland Fuels During Fire Season (Terrains with slopes less than 20 percent)

Wind Speed 20 ft. above ground in the open	Relative Humidity (percent)			
	Below 15	15 - 40	40 - 65	65 - 80
Below 5 knots	Dangerous	Dangerous	Low	Low
5 - 10 knots	Critical	Dangerous	Dangerous	Low
10 - 15 knots	Critical	Critical	Dangerous	Low
Above 15 knots	Critical	Critical	Critical	Dangerous

Definitions (for Table 3)

Low - irregular fire perimeter, spread greatly affected by changes in fuel structure and topography, depth of fire small. Fire generally stops at roads and ridge-tops. Control action can be on an individual basis.

Dangerous - continuous intense fire front which moves rapidly. Frequently spots ahead. Aggressive organised action required to protect personnel and equipment.

Critical - conflagration-type fire, in heavy fuels readily crowns and spots as much as a mile ahead. Control action only when changes in fuel type or burning conditions permit.

Notes (a) For heavy fuels, use the classification for next higher wind speed.

(b) For terrain with slopes greater than 20 percent, use the classification for the next higher wind speed.

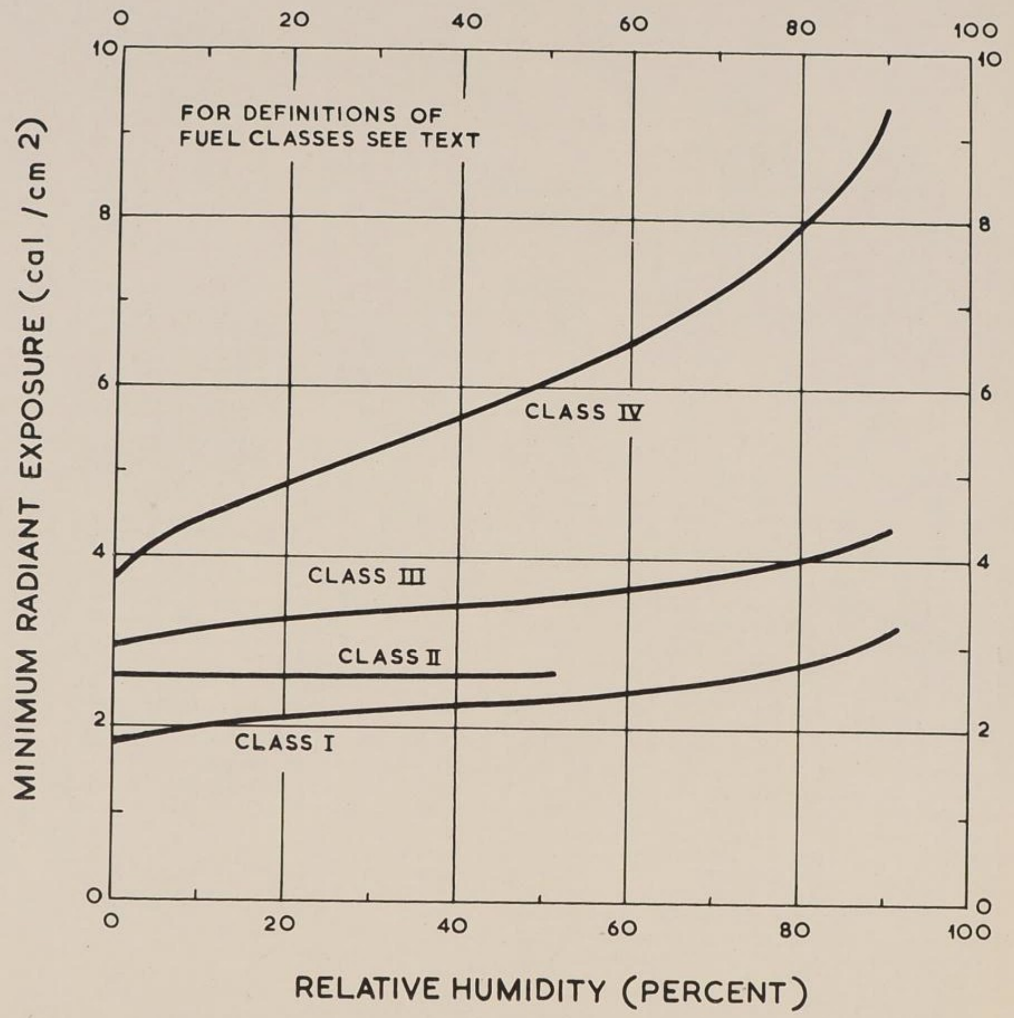
(c) For canopy shading 20 percent of the ground, reduce wind one class, and increase relative humidity one class.

(d) For full shading, reduce wind two classes and increase relative humidity two classes.

Details of damage to forests by airblast are given in Part III, Chapter 9, Section 9.9.

References.

(1) Capabilities of Atomic Weapons, (1957) U.S. Dept. of the Army TM 23-200. p.11-2. (Confidential)



MINIMUM RADIANT EXPOSURE FOR IGNITION OF WILDLAND KINDLING FUELS - SCALED TO 1KT

5.2. The Results of Atomic Weapon Tests on Forest Fuels

During the U.S. Atomic Weapon Test "Operation Snapper", measurements were made of the minimum thermal energies required to ignite common forest fuels, (Reference (1)). Observations were also made to determine blast wave effects on the persistence of ignition and to provide field data against which laboratory source tests could be scaled.

Prepared fuel beds of conifer needles, hardwood leaves, grasses and rotton wood, were exposed in Operation Snapper to total thermal energies varying from 1 - 22 cals/sq.cm. Thickness and density of fuel particles were determined prior to the test. Fuel moisture at shot time was measured in duplicate field beds, similarly located, but outside the test area.

Post test fuel examinations showed that decayed materials and fine grasses ignited and continued to burn at distances from Ground Zero where the total thermal energy was approximately 3 cals/sq.cm. Following shots 3 and 4, decayed materials were still burning upon recovery at H + 2 hours. The following conclusions were made ffom the test results.

(i) Under fire-weather conditions (relative humidity less than 40%, air temperature greater than 35°F, fuel moisture less than 15%) in a forest area, atomic explosiions can be expected to ignite decayed and fine grassy fuels wherever the total thermal energy exceeds 3 cals/sq.cm.

(ii) Minimum ignition energies have been established to within approximately ± 10% for common wild-land fuels - pine needles, hardwood leaves, grasses and rotted materials.

(iii) Rotted or decayed materials and fine grasses which are ignited at low energy levels by atomic explosions, can spread fire to associated fuels which would not otherwise have been ignited.

(iv) Sparse tree crowns exposed to energies of 22 cals/sq.cm. effectively shade dead surface fuels so that few ignitions of these fuels can occur in their shadow. Dense green forest stands, with 100% crown closure, should offer few, if any, ignition points where persistent ignition and fire would occur.

References

(1) Operation Snapper, Project S .1. The Effect of Atomic Explosions on Forest Fuels. WT-506, AFSWP. (Confidential)

5.3. Estimated Effects of Atomic Weapons on Forests of N.W. Europe

An assessment has been made (Reference (1)) of the general effects of exploding atomic weapons over forests, with particular reference to blast and fire hazards. The degree of protection likely to be afforded by forests in N.W. Europe to stores, vehicles and personnel in them, has been examined, and also the possibility of exploding atomic weapons over forests in order to create obstacles to the movement of tracked and wheeled vehicles and personnel, has been assessed. Two areas in which obstacle belts might be created in forests were examined in detail; the area to the S.W. of Kassel, and the area between Uelzen, Gifhorn, and the Eastern Frontier.

The main conclusions reached in the Paper were:-

(i) The range for ignition of forest fuels by thermal radiation from atomic weapons will exceed the range of blast damage under fine weather conditions, but when the weather is not fine, blast damage becomes of major importance.

(ii) The probability of fires started by the ignition of forest fuels spreading and leading to a general conflagration is small at all seasons of the year in W. Europe, but limited danger periods may exist during spells of dry weather, especially in the spring and autumn.

(iii) Forests can provide useful protection against the thermal effects of atomic weapons, the amount of thermal shielding being proportional to the projected area of foliage between the weapon and the target. All the year round protection is available in the coniferous forests which make up 70% of the total in Germany, the deciduous forests can only provide thermal shielding when in leaf.

(iv) Forests provide little in the way of blast protection to man and material in them. Rather, falling trees and branches and other secondary blast effects may hurt or damage men and equipment at ranges where they would be unaffected in the open and may also prevent access to stores or equipments in woods attacked by atomic weapons until such time as a major clearance effort can be made. (See Part III, Chapter 9, Section 9.9 for details of blast damage to forests).

Reference

(1) The Effects of Atomic Weapons on Forests in N.W. Europe.
Operational Research Section, B.A.O.R. Report 3/56 (Confidential)

CHAPTER 6 - THERMAL DAMAGE TO BUILDINGS AND URBAN AREAS

6.1 Origin of Fires

There are two general ways in which fires can originate from a nuclear explosion. Firstly, by the ignition of paper, rubbish, window curtains, awnings, dry grass and leaves etc., as a direct result of the absorption of thermal radiation. And secondly, as an indirect effect of the destruction caused by the blast wave, fires can be started by upset stoves and furnaces, electrical short circuits and broken gas pipes. No matter how the fire originates, its subsequent spread will be determined by the amount and distribution of combustible materials in the vicinity. It will be seen therefore, that the development of fires accompanying a nuclear explosion depends on two factors; firstly, the number of points at which fire originates, and secondly, the character of the surrounding area.

A study of the mechanism of initiation and development of fires from a nominal (20KT) atomic bomb is made in Reference (1). It is concluded that primary fires were much more numerous than secondary fires after the atomic weapon bursts in Japan, and that a large number of primary fires would probably result from an atomic burst over a British city. The simple precaution of preventing the entry of heat flash through window openings would greatly reduce the risk of primary fires from an atomic bomb. The Hiroshima fire storm must therefore have been due to primary fires. Normal scaling of the figures given in Reference (1) suggests that the fire zone could extend beyond the blast damage zone in the case of megaton weapons burst over cities.

Reference (1) also examines the incidence of secondary fires from H.E. bombs in the United Kingdom and in Japan, and a detailed account of secondary fires from the fly bomb attack on London in 1944 is given. From this evidence it is deduced that one nominal atomic bomb on a British city would probably start about 300 large secondary fires requiring the attention of the Fire Service, and about 1,000 small debris fires which could easily be extinguished by fire guards, if they did not go out of their own accord. This is not a serious fire situation, and could hardly give rise to a fire storm comparable with that at Hiroshima (see Section 6.2.2 of this Chapter), since this would require about 10,000 large initial fires in the damage area.

The fact that accumulations of combustible rubbish close to a wooden structure represent a real fire hazard was demonstrated at the nuclear tests carried out in Nevada in 1953. In these tests, three miniature wooden houses each having a yard enclosed with a wooden fence, were exposed to 12 cals/sq.cm. of thermal radiation from a weapon of about 30KT. The first house had weathered siding showing considerable decay, but the yard was free from rubbish. The second house also had a clean yard, and further, the exterior siding was well maintained and painted. In the third house the siding, which was poorly maintained, was weathered, and the yard was littered with rubbish. Following the explosion, the third house soon burst into flame and was burnt to the ground. The first house did ignite but it did not burst into flame for 15 minutes. The well-maintained house with the clean yard suffered scorching only. It was also noted that the wood of a newly erected white-painted house exposed to about 25 cals/sq.cm. was badly charred but did not ignite, (Reference (2)).

The incidence of wooden houses is very small in the United Kingdom and so the possibility of ignition from the outside is not nearly so great as in

this American test. However the test also showed that the radiation entering through windows caused combustion inside the houses, and this was sustained in the case where much combustible material was lying about, but died out in a tidy room with a low combustible content.

Critical energy data for various combustible materials are given in Section 4.2, Chapter 4, and some further values, given in Table 1 below, are taken from p.307 of Reference (3).

Table 1

Thermal Energies for the Ignition of Household Materials

Material	Weight (oz/sq.yd.)	Ignition Energy (cal/sq.cm.)	
		20 kilotons	10 megatons
Dust mop (Oily, grey)	-	3	5
Newspaper, shredded	2	2	4
Paper, crepe (green)	1	4	8
Newspaper, single sheet	2	3	6
Newspapers piled flat, surface exposed	-	3	6
Newspapers, weathered, crumpled	1	3	6
Newspaper, crumpled	2	4	8
Cotton waste (oily, grey)	-	5	8
Paper, bond typing, new (white)	2	15	30
Paper, Kraft, single sheet (tan)	2	7	14
Matches, paper book, blue heads exposed	-	5	9
Cotton string scrubbing mop, used (grey)	-	6	10
Cellulose sponge, new (pink)	39	6	10
Cotton string mop, weathered (cream)	-	7	13
Paper bristol board, 3 ply (dark)	10	8	15
Paper bristol board, 3 ply (white)	10	12	25
Kraft paper carton, flat side, used (brown)	16	8	15
Kraft paper carton, corrugated edges exposed, used (brown)	-	12	25
Straw broom (yellow)	-	8	17
Excelsior, Ponderosa pine (light yellow)	2 lb/cu.ft.	5	12
Tampico fibre scrub brush, used (dirty yellow)	-	10	20
Palmetto fibre scrub brush, used (rust)	-	12	25
Twisted paper, auto seat cover, used (multicolor)	13	12	25
Leather, thin (brown)	6	*15	*30
Vinyl plastic auto seat cover	10	*16	*27
Woven straw, old (yellow)	13	*16	*33

*Indicates material was not ignited to sustained burning by the incident thermal energy indicated.

Since thin kindling materials quickly reach equilibrium with the moisture condition of the atmosphere, the relative humidity has a marked effect on the critical ignition energy of any such fuels. Under conditions of high humidity, the ignition energy may be increased by 30 to 50 per cent.

There is another point in connection with the initiation of fires by thermal radiation which needs consideration. This is the possibility that the flame resulting from the ignition of a combustible material may be subsequently extinguished by the blast wind. It was thought that there was evidence for such an effect from an observation made in Japan, but this may have been an exceptional case. The matter has been studied both in connection with the effects in Japan, and at various nuclear tests, and the general conclusion is that the blast wind has no significant effect in extinguishing fires. (Reference (3), p. 319).

References

(1) Home Office Report CD/SA 6 - "The Atomic Bomb as a Fire Raiser - a Study of the Mechanism of Initiation and Development". (Secret).

(2) U.S. Civil Defence Administration Film,

"The House in the Middle".
(Home Office Film Library).

(3) The Effects of Nuclear Weapons, U.S.A.E.C., 1957.

6.2 Fire Spread

6.2.1 Local Fire Growth

Once ignition has occurred, a material continues to burn if sufficient heat is transferred to it from the flame. The amount of heat required depends upon the amount of moisture present in the material and the thickness and shape of the specimen. For example, thin splints of wood or thin films continue to burn after ignition, whereas boards one inch thick do not. Supplementary heat is required from external sources which, in the early stages of an ordinary fire, is often supplied by the igniting source. This supplementary heat does not normally exist in atomic explosions, and so a thick material isolated from other surfaces, goes out.

If flame persists and spreads over the surface of ignited materials, it is possible that other combustible materials in the vicinity may be ignited. The more objects that are ignited the greater the rate of supply of heat to both burning and unburnt materials. The materials already burning may burn more fiercely, and any remaining unburnt material in the room may very quickly be exposed to a rate of heat that may cause it to ignite. At this stage the fire spreads rapidly through the room. This is often referred to as the 'flashover'. If the walls or ceiling are made of combustible building boards, or the room has a high surface area of combustible material, this stage is reached more quickly.

Following the atomic explosions at Hiroshima and Nagasaki, once the fires had started there were several factors directly related to the destruction caused by the explosions that influenced the spread of fires. By breaking windows and blowing in or damaging fire shutters, by stripping wall and roof sheeting, and by collapsing walls and roofs, the blast made many buildings more vulnerable to fire. Non-combustible (fire-resistive) structures were often left in a condition favourable to the internal spread of fires by damage at stairways, lifts, and in fire-wall openings, as well as by the rupture and collapse of floors and partitions. On the other hand, when combustible frame-buildings were blown down they did not burn as rapidly as they would have done had they remained standing. Further, the non-combustible debris produced by the blast frequently covered and prevented the burning of combustible material. There is some doubt therefore, whether, on the whole, the effect of the blast damage was to facilitate or hinder the development of fires at Hiroshima and Nagasaki.

6.2.2. Mass Fires

In peace-time, the term 'conflagration' is often used loosely to describe fires burning in several adjacent buildings simultaneously. Even though fire spread may occur from these buildings to other adjoining ones, such fires are unlikely to spread to any great distance because of existing fire breaks and intensive fire-fighting. Mass fires of the type to be expected in the event of atomic attack, on the other hand, are great fires burning entirely out of control. These fires have the greatest potential as destroyers of life and property and are of such an extensive nature that consideration of fire risk to an individual building or small group of buildings becomes meaningless. Mass fires which have been observed in the past consist of two types, fire storms and conflagrations.

Fire storms are expected on the rapid ignition of large areas in the absence of a strong ground wind. In such a case the interacting fire winds started by the many individual fires merge the aggregate blazes into one inferno with its own pillar of burning gases rising almost vertically above the centre of the ignited area. The rapid rise of hot and burning gases causes an influx of new air at the base of the pillar. This on-rush of air, or fire wind, reaches gale-like proportions as it heads towards the fire centre, where sufficient fuel is available and no large fire breaks are found. Such fires raise to the ignition point all combustibles, and complete burnout within the affected area follows. Even where no burning occurs, the fire wind collapses buildings, uproots trees, and sends objects as large as motor-cars spiralling into the air. However, since all winds blow towards the centre of the fire, there is usually little fire spread to the areas beyond those originally affected. A description of a fire storm which developed in Hiroshima about 20 minutes after the detonation of the nuclear bomb, is given in Reference (1).

A conflagration, on the other hand, is a great fire which moves along the ground under the influence of strong winds. In this case the initial fires, in merging, spread considerably to leeward. The pillar, once it has been established, slants appreciably to leeward, and large numbers of firebrands are showered upon the leeward region. Also, the higher the wind velocity, the more the pillar leans and the closer the hot and burning gases approach combustible materials on the ground. The chief characteristic of the conflagration therefore, is the presence of a fire front, an extended wall of fire moving to leeward preceded by a mass of pre-heated turbid burning vapours and by a large number of spot fires initiated by the firebrands. The progress and distributive features of the conflagration consequently may be much greater than those of the fire storm, for the fire continues to spread in the downwind direction until it can reach no more combustible material.

Initiation and spread of these mass fires following enemy attack depend to a large extent on the fire susceptibility of an area. The fire susceptibility, in turn, is influenced not only by the presence of the kindling fuels already discussed, but also by the presence and spacing of all combustible materials in the area. Thus, the ignition point is of concern only if sufficient contiguous fuel is available to ensure the formation of a growing fire. For this initial fire to be of major importance it must burn long enough to permit spread to additional combustible material nearby. Consequently, fuel factors which affect fire susceptibility in conventional (industrial) fires are also of importance in consideration of thermal vulnerability to atomic explosions. Among these important factors are size and combustibility of structures, fuel value of

building contents, continuity of combustible construction, and the presence of fire breaks.

A British scheme for the zoning of towns for fire susceptibility is described in Reference (2). This scheme has now been applied to the major towns in the United Kingdom. Fire zone maps have three important uses:-

(i) They indicate where large area fires are possible, and where efforts to reduce fire risk should be concentrated.

(ii) They provide a standard basis for schemes for emergency water supplies, and for the development of wartime fire-fighting tactics.

(iii) They are a guide for those concerned with the problems of shelter and evacuation.

The curve in Figure 1 gives a rough idea of how the probability of fire spread, expressed as a percentage, depends upon the average distance between buildings in a city. (Reference (1), p.321). The results will be dependent, to some extent, upon the types of structures involved, e.g. whether they are fire-resistive or not, as well as upon the damage caused by the blast wave. It should be noted that Figure 1 applies to fire spread accompanying a nuclear explosion, when a large number of small fires are started directly by thermal radiation and indirectly in other ways.

References

(1) Effects of Nuclear Weapons, U.S.A.E.C., 1957.

(2) Home Office Report CD/SA.21. "The Zoning of Towns for Fire Susceptibility". (Secret).

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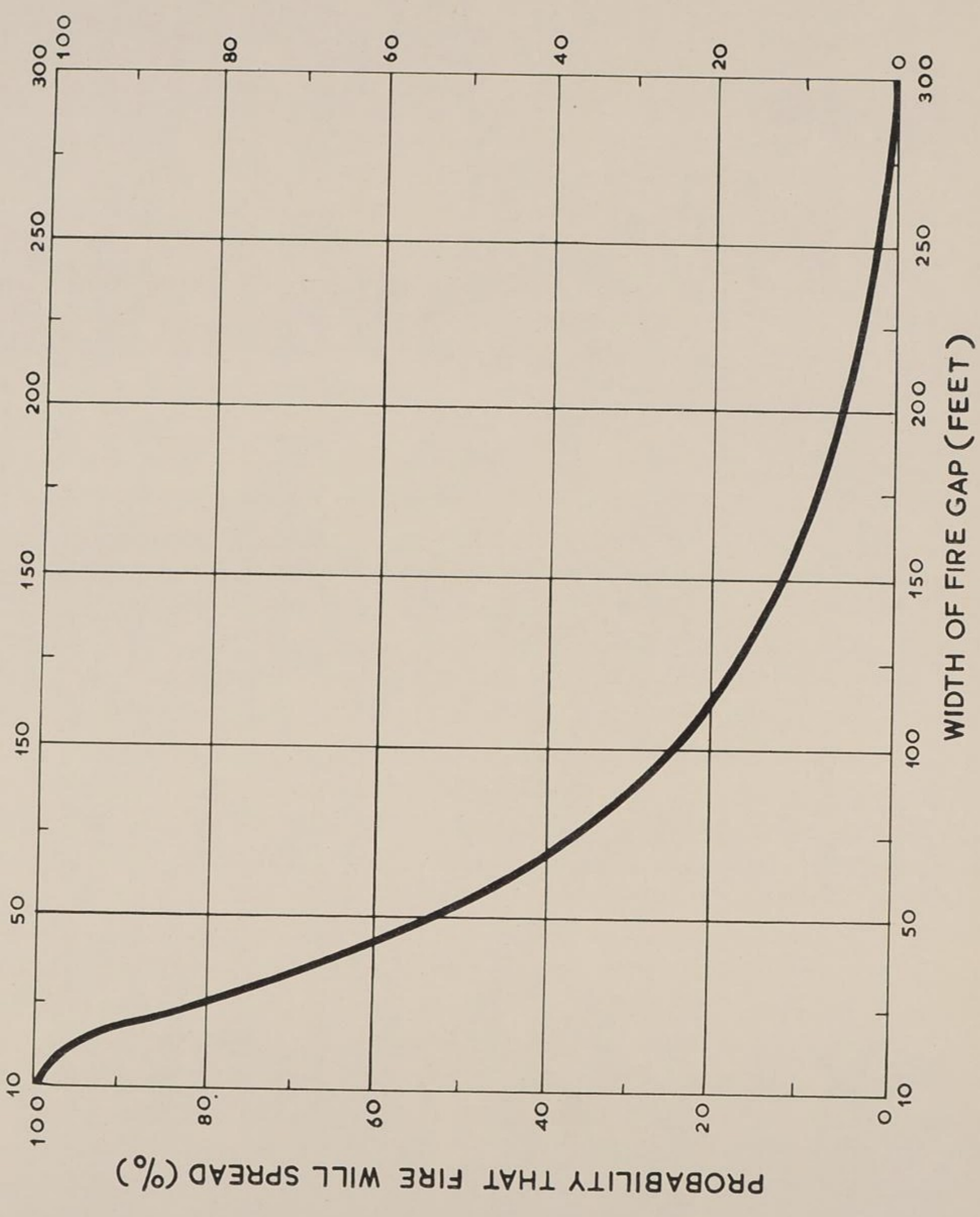
PART VI
CHAPTER 6
SECTION 6.2.2
FIGURE 1



PROBABILITY OF FIRE SPREAD ACROSS
GAPS IN BUILT-UP AREAS

6.3. Fire Control

From what has already been said about the scope of fire storms and conflagrations, it is obvious that much fire control action must be taken prior to the start of the fire. An important first step is, of course, the elimination of all exposed kindling fuel, either by removal of the fuel or by shielding it from exposure to a thermal flash. A second important step is the elimination or dispersal of all combustible materials. Some other factors which may influence fire control will now be considered.

(i) Effect of weather

The weather, prior to and during the detonation of a nuclear weapon, will have an influence on fire control and, in the case of grass, brush and woodland fires, information concerning weather conditions is useful in evaluating probable fire behaviour. (For details of thermal damage to vegetation see Chapter 5.). Based upon weather conditions, four classes of burning potential are recognised - low, moderate, dangerous and critical. These burning potential classes, and the probable fire effects of each, are shown in Table 1, taken from Reference (1).

/Table 1

Table I - Burning Potential and Fire Effects

Burning Potential	Type and Rate of Spread	Civil Defence Requirements
Low	Slow burning fires, no spotting	No direct danger; fire can be controlled at will; control action can be on an individual structure basis. Organised action needed to corral fire and confine to area originally ignited.
Moderate	Fires burn rapidly, individual building fires combine to form an area fire	ditto
Dangerous	Fast-moving fires which spread readily over large areas and throw spot fires ahead $\frac{1}{4}$ to $\frac{1}{2}$ mile	Probability of mass damage high. Aggressive, organised action of all available personnel and equipment is essential to limit mass damage.
Critical	Conflagration-type, fast-moving fire fronts and fire storm highly probable.	Personnel and equipment should be evacuated from in front and from near the flanks of such fires. Organised action only on rear and flanks with plants to attack head when changes in fuel or burning conditions permit.

The effects of wind and relative humidity on the burning potential have been roughly integrated into Tables 2 and 3.

Table 2 - Burning Potential in Relation to Relative Humidity and Wind - Level Terrain (slopes less than 20 per cent)

Wind Velocity at 20ft. Above Ground (m/hr)	Relative Humidity			
	Above 40	26 to 40	15 to 25	Below 15
0 to 12	Low	Moderate	Moderate	Dangerous
13 to 24	Moderate	Dangerous	Dangerous	Critical
Above 24	Dangerous	Dangerous	Critical	Critical

Table 3 - Burning Potential in Relation to Relative Humidity and Wind - Steep Terrain (slopes greater than 20 per cent)

Wind Velocity at 20ft. Above Ground (m/hr)	Above 40	26 to 40	15 to 25	Below 15
0 to 12	Moderate	Moderate	Dangerous	Critical
13 to 24	Dangerous	Dangerous	Critical	Critical
Above 24	Critical	Critical	Critical	Critical

As may be seen from these Tables, the presence of a strong wind is of prime importance in assessing the burning potential. In the case of the mass fires expected in atomic attacks, strong fire winds will probably assure the existence of wind velocities much greater than 24 miles per hr. The presence of prior strong winds however, will be important in determining whether the mass fire will be of the fire storm or conflagration variety. With the exception of these wind effects, weather does not play as large a role in fire effects of atomic attacks as has been frequently assumed. Clouds, fog and precipitation may influence the extent of fire damage by attenuating the thermal radiation pulse (for details see Section 1.2.2. of Chapter 1), and also by creating conditions favourable to the high moisture content of fuels. However, the kindling fuels are quite thin and respond rapidly to changes in humidity. Thus a very short period of sunshine is sufficient even after heavy rain, to dry out many of these fuels. In fact, the energy in the thermal pulse itself is frequently sufficient to dry out and then ignite the kindling fuel at only a slightly higher calorific level than would have been required had the fuel been dry.

Once a good fire has been started, it can readily overcome the retarding effect of moisture in heavier fuels. Therefore high humidity during the period preceding the attack is important only in the initial stages of the fire. If this obstacle to fire initiation is overcome, humidity will be of minor importance in retarding fire propagation and spread. In fact, studies conducted during the last war indicate that even when rain was falling, during conventional fire bomb attacks, the damage produced averaged only 20 per cent less than that produced under weather conditions favourable to the attack, (Reference (1)).

In the case of atomic attack, a heavy rainfall during the attack period will be extremely effective in reducing ignitions in kindling fuels exposed to the weather, but will not noticeably alter the ease of ignition of protected materials inside a building. The outer walls of buildings if soaked with moisture, will resist fire spread longer, and give time for organised fire defences to act. Snow does not hamper the spread of fire to the same extent as does rainfall, because the side walls of buildings do not become water-soaked. Snow on the roof, if melted by a fire, tends to run off through channels without wetting down the walls to any great extent.

(ii) Water Supplies

Sprinkler systems have been highly successful in the past in combating conventional fires. However, they usually only cover the contents of buildings; they are not activated until fires have had an opportunity to become established; and they operate at a capacity inadequate to handle a large scale disaster. Sprinkler systems as they are now used are designed to handle the opening of a small fraction of the sprinkler heads in any one building at any one time. Neither the water supply nor the piping system permits simultaneous operation of any large number of sprinklers without extreme loss in effectiveness. Thus the opening of a large number of sprinkler heads by the widespread fires resulting from atomic attack would most probably limit the output at each head to a mere trickle.

Failure of water systems during atomic attack is to be expected, not only for sprinkler systems, but for practically all types of conventional fire-fighting methods. Thus at Hiroshima, for example, even though the water reservoir was undamaged, 70,000 breaks of pipe connections in buildings and dwellings were caused by blast and fire effects, and consequently the pressure in the mains dropped to zero. Even when the water system is not disrupted, experience in fighting war time mass fires in the past has indicated that a professional Fire Department using conventional technique is useless except on the fringes of the fire (Reference (1))

Much of the fire-fighting equipment has been lost in an attack; debris-littered streets have prevented the entry of fire-fighting equipment where it was needed; strong fire winds have made even motion next to impossible; and failure of communication systems has led to almost complete confusion.

Where a built-up area adjoins a large body of water, use may be made of an item of fire-fighting equipment which appears to provide the best chance of surviving an attack and being utilised in subsequent fire-fighting action - the fire boat. It is equipped with its own pumping facilities, is flexible in its uses, and may be moved anywhere along the waterfront area where it can be effectively used. Another conveyance which is extremely useful in mass fire situations is the helicopter. Its use for rapid reconnaissance of the fire area is obvious and in addition, recent work has indicated its great potential as a carrier of water, chemicals and equipment in perimeter fighting of large-scale forest fires. (Reference (1)).

(iii) "First Aid" Fire Fighting

Most ignitions by thermal radiation are quite small and readily extinguishable if caught early; they are serious because there are so many of them. In the initial phases, these fires may be extinguished with minimal equipment. They may be stamped out by foot or dealt with by conventional fire extinguishers. Where the number of primary ignitions is relatively small, and sufficient manpower is available for prompt action, the subsequent spread of fire from a doomed area may be prevented. Similar techniques would be useful in fighting the spot fires started by firebrands which may jump fire breaks.

(iv) Flame-Retardant Treatments

The treatment commonly applied to materials to reduce the fire hazard may be divided into two categories - surface treatments and impregnation treatments. In choosing a particular treatment, matters other than their efficiency as fire retardants must be considered. For example, few treatments are suitable in exterior conditions, so that normally only interior combustibles can be treated, and even then many treatments affect the working qualities of timber or corrode metal fastenings.

Some paints, based on urea formaldehyde resins and monoammonium phosphate, when exposed to heat, bubble up to form an aerated non-flammable coating of low thermal conductivity which protects the material for some time. Other paints, such as those based on sodium silicate, give protection by providing a vapour proof membrane round the material. In the same class are those which use an incombustible insulating material such as asbestos or mineral wool. These are usually mixed with a binding solution and applied in a thick layer. A thin layer of asbestos paper completely covering the combustible material, is probably as effective as many of the best paints. A different type of protection is given by paints of the calcium sulphate type which hold the temperature of the material at 100°C until their water of crystallisation has been removed.

To impregnate timber, a number of salts may be used. The most efficient and also the most commonly used salt is monoammonium phosphate; others are boric acid, ammonium chloride, ammonium sulphate, magnesium chloride, and zinc chloride. Ordinary white distemper is quite effective in delaying ignition, doubling the quantity of heat required for the ignition of fibre insulating board, while phosphate resin paint is even more effective. These treatments increase the difficulty of ignition and initial spread of flame, (Reference (2)).

References

(1) Report U.S.N.R.D.L., TR-101 (1955) "Thermal Vulnerability of Military Installations"

(2) Hird, D, and Simms, D.L., "Fire Retardant Paints", Wood, March, 1953, pp 92-95, April, 1953, pp 134-137, May, 1953, pp 176/177.

CHAPTER 7 - BIOLOGICAL EFFECTS OF THERMAL RADIATION

7.1 Introduction

The radiant heat emitted by the air burst atomic explosions over Japan caused a large number of casualties through burns of the skin directly exposed to it; these are known as flash burns. These injuries were noted in early reports, but their importance tended to be overlooked compared to radiation sickness, until the Bikini trials. Many of the Japanese flash burn casualties died of shock or other wounds, and flash burns among survivors became grossly infected due to ignorance, and the breakdown of medical services. Consequently, survivors showed exaggerated scars (keloids). These effects, coupled with the delay before flash burn survivors were closely interrogated and examined, meant that the course of treated uninfected flash burns was unknown. The present account of the response of man to thermal radiation falling on his skin must therefore be built upon the results of subsequent experimental studies in the laboratory.

In the assessment of burn injuries, the percentage of body surface involved is important as indicating the extent to which life is threatened, particularly by "surgical shock." If over 60% of the body surface is burnt, recovery is unlikely; if under 20% of the body surface is burnt, recovery should be certain in the absence of complicating injuries. Such methods as the "Rule of Nine" (Reference (6)) are used to estimate these percentages.

Since 1949, the problems of flash burns have been reviewed (References (1), (2)) and investigated (References (3), (4), (5)). It is obviously much easier to conduct flash-burning studies on animals than on man, and a much larger number of experiments on animals have been performed. However, serious errors can arise from using the results of animal experiments to deduce effects in man. The present review (sections 7.2 to 7.7) will therefore be based as far as possible on the results of investigations of flash burns in man.

Much of the energy released in a nuclear explosion appears in the form of ultra-violet, visible and infra-red radiations. The preretinal media of the eyes, i.e. cornea, aqueous, lens and vitreous, are together opaque to ultra-violet radiations, but they do transmit most of the visible spectrum and a large part of the infra-red. Consequently, these are the radiations potentially capable of affecting the retina. In fact, the thermal radiations from a nuclear weapon may affect the eye in two ways - burns on the retina causing a permanent visual defect, and temporary flash-blindness. Burns on the retina (chorioretinal burns) are discussed in Section 7.8.1, and flash-blindness in Section 7.8.2.

References

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(4) Evans, E.I., Brooks, J.W., Schmidt, F.H., Williams, R.C., and Ham, T.R. Jnr. "Flash Burn Studies on Human Volunteers." Surgery, 1955, 37:280.

(5) Pearse, H.E.. and Kingsley, H.D. "Thermal Burns from the Atomic Bomb." University of Rochester, New York. Atomic Energy Report UR-254, pp.1-42, April 30th, 1953.

(6) The Nuclear Handbook for Instructors and Staff Officers - Page 192. War Office Code No. 9405, Air Publication AP3321. (Restricted).

7.2 Flash Burns in Man

7.2.1 Local Effects in the Skin.

As already noted in the case of materials, the thermal dose required to cause a given response in the skin depends upon the rate of delivery, being less for the faster deliveries. The doses of radiant heat considered here range up to about 5 cals/cm^2, delivered in about 0.5 seconds, characteristic of a 20 KT bomb. For doses corresponding to other durations, see Section 7.5.3. These doses would not cause burns through clothing, nor flame burns through the ignition of clothing, though such complications would arise with higher dose levels at shorter ranges. Thus, the flash burns described below would involve only uncovered skin, that is the face, neck, hands, wrists and forearms in men, and also the legs in women and children exposed directly to the heat flash and unsheltered by buildings, etc. It should be noted that there may be variations between individuals in their susceptibility to flash burning, and this is discussed later in Section 7.3.1. (d).

At considerable distances from the weapon, sensations of warmth or heat will be felt when a sufficient dose of radiant heat falls on the exposed skin. These sensations are of no serious import.

An immediate intense brief stinging pain, localised in the exposed area, will be felt when a sufficient dose of radiant heat from an atomic explosion falls on the skin. If the dose of predominantly white light is less than some 1.5 cals/cm^2, no signs of burning will follow. As the range shortens and the dose approaches about 2.0 cals/cm^2, here taken as the threshold for significant first degree burns, this stinging sensation subsides and is followed after about 30 seconds by an erythema (redness) of the exposed area, together with the changes listed below.

(a) 1st Degree Flash Burns (Dose 2-3 Cals/cm^2 in 0.5 seconds)

The erythema increases for about an hour. It is by then surrounded by a flare, that is a pinkness of the skin induced by local nerve stimulation, which extends for about 2 cm. beyond the edge of the burned area. There is a dull burning pain, and the flare persists from a few minutes up to several hours. The burning pain is felt for up to 24 hours.

After the first day the burned area remains reddened and sore to touch, for as long as eight days. Peeling of the fine flakes of skin epidermis (superficial skin layers) follows, and during the next few weeks the burned area becomes pigmented. Such burns do not disable seriously, but involvement of the hands would impair efficiency for manual tasks.

(b) 2nd degree flash burns - (shallow partial skin loss flash burns - typical dose approximately 3-4 cals/cm^2 in 0.5 secs)

In these burns the changes are at first similar to those for the slighter first degree burns, except that the skin is discoloured by singed hair, and the dull burning pain is more intense.

By one hour after burning, oedema is visible, localized to the exposed area. By two to thirty hours, depending in part upon environmental conditions, the burned area blisters. The blisters ache and ooze serum for three to four days, after which the burn is covered by a dry scab. This separates after

/about

a week providing infection has been excluded, otherwise the burned area shows pus. If the burn is uninfected, dilated blood vessels, filled with cyanotic (blue) blood, are visible after the scab has been removed.

In such burns, healing (in the absence of infection) takes place from the skin cells surviving deep in the hair follicles and sweat glands; thus, epithelialization (re-covering of the burn with new skin) occurs evenly from within the burned area and not from the edges. These burns are tender to pressure and are easily injured for 8-14 days. If such shallow flash burns become infected, surviving skin elements are destroyed and healing is greatly delayed; a small burn accidentally infected in the laboratory took six weeks to heal.

Incapacitation would not be complete with uninfected shallow blister flash burns unless palpebral (i.e. of eyelids) oedema and oozing interfered with vision. Oedema of the face and lips might necessitate a liquid diet. Manual dexterity would be restricted by such burns of the hand. During the first one or two days the burning pain of such flash burns over extensive areas would be distracting. It seems to have been this sensation which led Japanese casualties to apply compresses to their burns in search of relief.

(c) Second degree flash burns (deep, partial skin loss flash burns, typical dose 4-5 cals/cm^2 in 0.5 seconds.)

Nearer to the explosion, closing to the range of 3rd degree flash burns (see below), the radiant heat falling on the skin would cause intense local vasoconstriction (shut-down of the blood vessels) with consequent blanching immediately after the explosion. The surface of these burns is anaesthetic to pinprick at this stage. The blanching gives way to erythema after about a minute, following which the cource is essentially similar to that described above for shallower 2nd degree flash burns, except that, even in the absence of infection, healing is not secure until three to four weeks. Incapacitation would be correspondingly prolonged.

(d) Third degree flash burns (whole skin-loss flash burns, typical dose over 5 cals/cm^2 in 0.5 seconds)

Closer to the explosion, those parts of the exposed skin which suffer normally incident or nearly normally incident thermal radiation, would be injured to such a depth that no skin cells would survive deep in the hair follicles or sweat glands. Under these circumstances, the skin cannot heal itself except by growth for short distances from the surviving edges. The importance of this state of affairs is that scars will inevitably form over burned areas. Such scars, months or years later, contract and become hard, both of which tendencies prevent normal movement and proper function of skin and joints. It is to avoid this scarring that modern treatment covers the burned areas with skin grafts, whose growth inhibits scar formation beneath them.

In 3rd degree flash burns, the brief stinging pain is also followed by blanching. The margins of the burned area pucker due to the contraction of the burned area. The tissues below and around the burned skin swell during the next hour. This oedema lasts for two days or so. By this time, blisters have become discernible at the edge of the 3rd degree burn. The central 3rd degree burn remains sore to touch for 7 to 10 days and is tender to pressure until healed. By the fifth day after burning, the area begins to change from white to a pinkish hue. The dead burned skin spreads from the surrounding tissues during the third week and sloughs away during the fourth week. In the case of small experimental burns, healing takes place from the edges before granulations (the precursors to scars) are established at the base of the burn. It is to be expected that if such burns covered areas wider than 2 cms., sloughing would be followed by the formation of granulations. In that event, plastic surgery would be required to prevent scar formation and to restore adequate function by skin grafting. The time required for healing in such burns after an atomic bomb attack would therefore depend upon the medical and surgical resources available to treat them; the prevention of infection in such burns would enhance the chances that skin grafts would take and effect a satisfactory quick result. Infection would attack skin grafts in much the same way as it destroys surviving skin cells in hair follicles and sweat glands in shallower burns, and thereby increase the surgical procedures necessary to achieve healing.

Incapacitation from 3rd degree burns would obviously be greater and more prolonged than in shallower burns; it might include a period in a hospital. It is important to stress that, due to the curvature of the body, 3rd degree burns would be surrounded by regions of 2nd and 1st degree burning. Since there would be an additional area of flaring beyond, judgement of the extent of flash burns would be complicated.

(e) Superimposed effects on the skin

It is also to be expected that the appearance of flash burns when first seen would be masked by other effects arising from the attack; they would almost certainly be soiled by dust thrown up later by the blast wave; lacerations, bruises and abrasions might be superimposed. It seems probable that the recognition and accurate diagnoses of flash burns would be facilitated by adequate cleansing.

7.2.2 General Effects and Complications

The following are, strictly speaking, medical problems. They are considered in detail in various medical publications about flash-burning. They are mentioned here briefly to complete the description of 'target response', for this is more than skin deep in man.

(a) Early complications from burning injury - Immediately after flash-burning injury, the casualty may show one or more of a variety of reactions, so-called 'primary shock'. Some may faint or vomit. Others show symptoms of relief that they were not more seriously injured: they may show marked tremor of the hands, lips, face and even head. In the event of attack by atomic weapons, it is possible that panic may be added, especially if many fires are started or there are other startling consequences of the attack.

After a few hours, or even a day, a more serious derangement may ensue, so-called secondary shock. This is due to a reduction of the volume of fluid in the circulating system, the blood vessels. If the skin over 15-20%* of the body surface,) is burned 2nd degree or deeper, the amount of plasma lost can so deplete the blood volume as to be a threat to life. The body reaction to diminishing blood volume, is, firstly, to restrict the circulation to the hands, feet, nose and ears, which consequently feel cool compared to the rest of the body (N.B. they may feel cool in people lying in a cold environment). Next, the pulse quickens. If these measures fail to compensate for the plasma lost, the blood pressure will fall. The blood passing the kidneys is presently reduced, so that little or no urine is formed, and if the process continues, the mind becomes clouded with restlessness and coma unless treatment is instituted. All these changes can be reversed by adequate therapy; without therapy, death may ensue.

There is ample evidence from eye-witness accounts that this chain of events occurred among Japanese casualties. This may have been due to the scanty clothing worn by the population. But since a flash burn of a man in singlet and shorts would involve over 15% of his skin (or more if the prolonged flash from a larger weapon resulted in flash-burning of all unclothed skin), such a casualty would be likely to require special resuscitation and perhaps intravenous transfusion therapy.

(b) Later complications from burning injury - The later complications are usually the results of inadequate medical attention. Flash burns easily become infected. The body responds by making white cells (pus); again there is ample evidence that this occurred in Japan. The formation of large quantities of pus leads to a debility (from protein deficiency). The patients become anaemic and more susceptible to infection, so that a vicious cycle sets in causing very prolonged incapacitation and a poorer prognosis. These complications are prevented by excluding infection. It is possible, but more difficult and more expensive, to treat infections with drugs and antibiotics after they are established.

/The

*This is roughly equivalent to flash-burning a man in singlet and shorts.

The late complications of burns are scarring and the contraction of scars. These may take years to develop. The contracted scar can so impede movement as to cripple the patient. Such complications can be prevented by early skin grafting, or treated by exclusive plastic surgery. Again, late treatment is rarely as satisfactory as prevention.

(c) Injuries in addition to flash-burning - There remains also the possibility that flash burns may be complicated by other injuries. The casualty who has suffered a flash burn may receive a laceration, contusion, abrasion, fracture or penetrating wound as a result of the blast wave arriving a few moments later. Or, if the flash burn casualty is at a shorter range, or trapped in a burning building, he may have additional burns from ignited clothing or contact with both objects during his escape. Finally, under various circumstances, the flash-burned casualty may also suffer a serious dose of ionizing radiation. In a study of anaesthetised dogs, burned and irradiated with various doses of X-rays, it has been found that small doses of radiation (50r) made the animals more susceptible to infection in their flash burns. This could be counteracted by suitable antibiotic therapy. (See also Part VII, Chapter 2, Section 2.1).

7.3 Threshold Doses for Flash Burns

7.3.1 Factors Influencing Thermal Effects

Through knowledge of the threshold doses required to produce them, the range of the local effects in the skin (See Section 7.2.1) can be deduced from the thermal doses received from atomic explosions. These thresholds, and the parameters mentioned below, have been studied in various laboratories (e.g. References (1), (2) and (3)). The local changes described are consequent upon physical and chemical effects brought about in the superficial layers of the skin by the incident energy. The following factors may influence these effects.

(a) Spectral qualities of the incident radiation - Briefly, ultra-violet light (U.V.L.) is absorbed exclusively in the most superficial layers of the skin. Here it causes photo-chemical changes and the release of substances which produce reddening and blistering of the skin (cf. sunburn). It is unlikely that U.V.L. is important in flash-burning from atomic weapons since calculations indicate that it is absorbed by the atmosphere in comparatively short distances. Of visible light (V.L.) incident on the skin, about 50% is reflected. Some wavelengths in the visible band penetrate deeper in the tissues than U.V.L. or infra-red radiation (I.R.R.). The skin reflects about 10% of incident I.R.R., most of which is absorbed in the first 2 mm. of the tissues.

(b) Area of exposure - One of the problems in studying thresholds in the laboratory was selecting an aperture-size large enough to permit extrapolation to burns as large as the face or forearm and small enough to be acceptable for volunteers. In a study designed to investigate this point (Reference (4)), it was shown that in the case of 2nd and 3rd degree burns apertures 1 cm. in diameter provided a reasonably reliable basis for the thresholds which would obtain if larger areas were exposed. This was not true for sensations of warmth, heat and pain, and for 1st degree flash burns, for which endpoints it was found that increasing the area exposed reduced the threshold dose per unit area required to elicit the response. However, these latter endpoints have no serious clinical consequences (general effects), so that the area-dependence of thresholds is of more academic than practical importance.

(c) Duration of exposure - This is discussed later in connection with scaling laws (Section 7.5.3). The question has not been thoroughly investigated in man for reasons given there, but the effect of duration of exposure is regarded as negligible between the limits 0.3 and 1.0 seconds. It should be noted however that for a given thermal dose, as the weapon yield increases, the thermal radiation is delivered over a longer period of time and thus at a lower rate. This allows energy loss from the skin surface by conduction to the deeper layers of the skin and by convection to the air. Thus a given level of damage is also yield dependent. Critical radiant exposures for the production of two degrees of burn on bare skin, as a function of yield, are presented in Figure 1 (taken from Reference (5)) for

/normal

normal incidence of radiation. The curves represent those radiant exposures which will burn 50% of any group, allowing for the other variants discussed in this section.

(d) Individual variations in skin temperature, reflectivity, thickness, texture and hairiness

It is known that the local effects brought about by visible and infra red radiation are temperature dependent, because the threshold doses can be raised by artificially cooling the skin before experimental exposures. This factor might double the threshold doses for second degree burns in very cold conditions.

Variations in skin reflectivity are of more importance as between races than between individuals of like race. There is evidence that the dark-skinned races are more susceptible to flash burning than the white (guess 2:3), (Reference (6)).

All investigators have noted that the thicker coarser skin of males is slightly more resistant to flash burning than that of females. Children have not been studied and the effect of age is not known.

In Japan it was unusual for flash burning to occur through the hair of the head. However there is as yet no experimental evidence that the hairiness which occurs over the forearms affords any significant protection.

References

(1) Evans, E.I. et al. Flash Burn Studies on Human Volunteers. Surgery, 1955, 37:280.

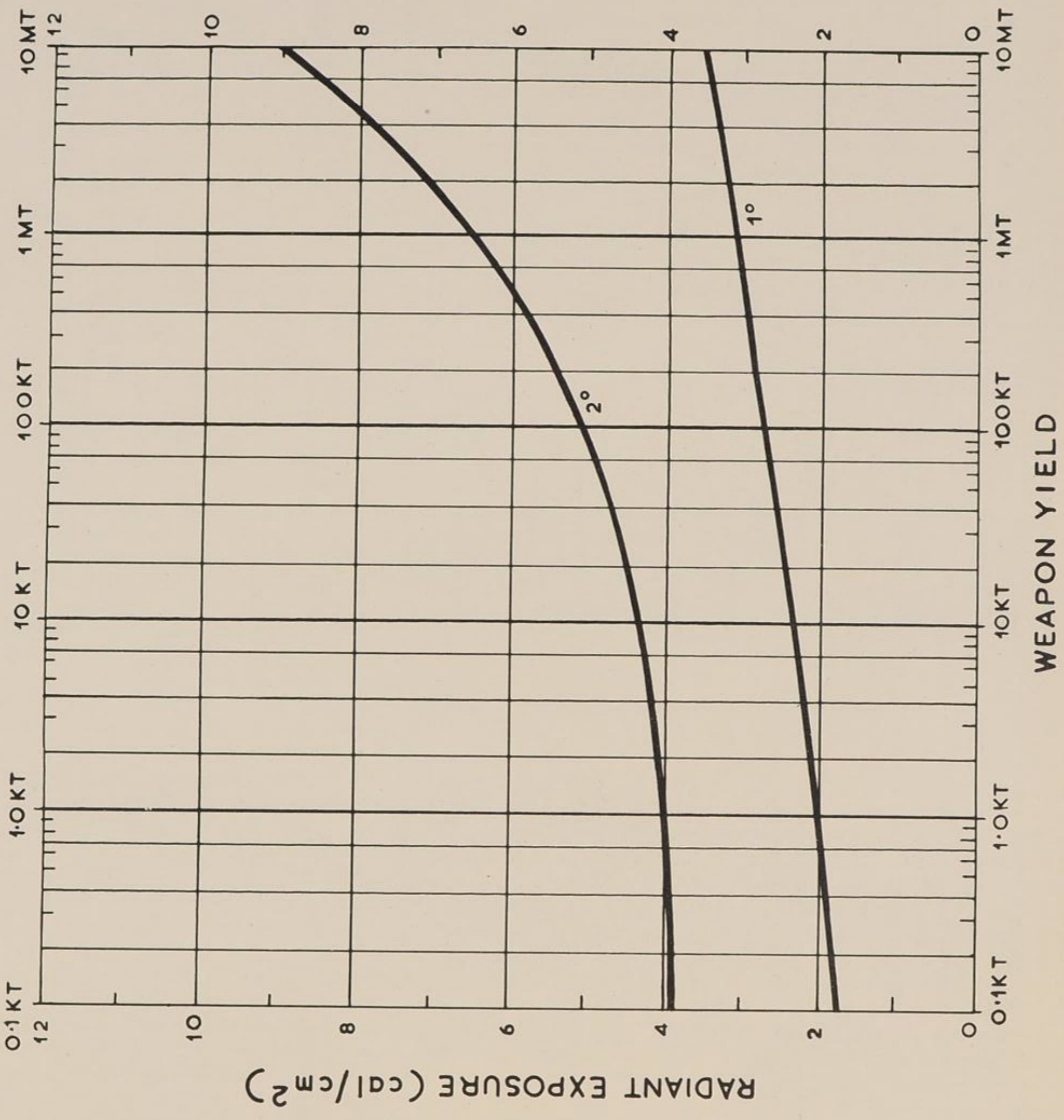
(2) Morton, J.H., Kingsley, H.D., and Pearse, H.E. Studies on Flash Burns : Threshold Burns. Surgery, Gyn.Obst. 1952, 94:317.

(3) Perkins, J.B., Pearse, H.E., and Kingsley, H.D. Studies on Flash Burns : the Relation of the Time and Intensity of Applied Thermal Energy to the Severity of Burns. University of Rochester, New York. Atomic Energy Report U.R.-217, pp 4-58, December, 1952.

(4) Butterfield, W.J.H. et al.. Flash Burns from Atomic Weapons, I. Observations on Flash-Burning of Human Subjects in the Laboratory using Infra-red and Predominantly White Light Sources. Surgery Gyn.Obst. 1956, 103:655-665.

(5) Capabilities of Atomic Weapons (1957), U.S. Dept. of the Army FM23-200. (Confidential).

(6) Kuppenheim, H.F., and Heer, R.R. Jnr. Spectral Reflectance of White and Negro Skin between 440 and 1000 mu. J.Appl. Physiol. 1952, 4:800.



CRITICAL RADIANT EXPOSURE FOR 1ST AND 2ND DEGREE BURNS ON BARE SKIN

7.3.2 Laboratory Studies of Threshold Doses

The results of some laboratory investigations (References (1), (2) and (3)) into threshold doses for various effects, are given in Table 1. Essential details of the experimental methods are also given.

TABLE 1 - 50% Probability Threshold Doses (Cals/cm^2)

Key to Exptl. Methods (See below)	Thermal Radiation Type	Aperture Diameter cm.	Exposure Time secs.	Dose in Cals/cm^2				
				Pain	1st Degree Flash-burns	2nd Degree Flashburns		3rd Degree Flash-burns
						Shallow	Deep	
(i)	IRR	5	1.0	<0.7	< 1.5	2.1	-	-
		3	1.0	0.75	1.5	2.1	-	-
		1	1.0	>0.8	> 1.5	2.1	-	-
(ii)	(Predominantly Visible)	1	0.17-0.45	-	2.0	3.0	4.0	5.25
(iii)	(")	1.8	0.3	-	1.3	2.8-3.2	-	<<8
(iv)	VL & IRR	1.1	0.54	-	2.0	3.2	3.9	4.2

(a) Experimental methods

(i) Source - Gas-fired radiant panel, surface temperature 1000°C. The emission spectrum is shown in Figure 1A together with curves for transmission of skin surface and penetration beyond 2mm.

Calibration - Copper block and special radiometer.

Subjects - 8 males, 20-32 years of age. Site - Forearms. Unshaven skin.

(ii) Source - Unfiltered beam from carbon arc. The emission spectrum is shown in Figure 1B together with curves for transmission of skin surface and penetration beyond 2 mm. Squarewave input.

Calibration - Copper block and bolometer.

Subjects - 7 males, 20-32 years of age. Sites - Forearms and wrists. Unshaven skin.

(iii) Source - Unfiltered beam from carbon arc. Squarewave input.

Calibration - Copper disc and special radiometer.

Subjects - 7 males. Sites - Arms and legs.

(iv) Source - Carbon arc, UVL filtered off by Corning Filter 0-53 with cut off below 3200A. Pulse form input.

Calibration - Flow calorimeter and copper disc.

Subjects - 12 males, 2 females. Site - Outer aspects, shoulders and upper arms.

(b) Conclusions

There is good agreement between the various investigators using carbon arc sources. The IR results quoted are the only data available from investigations using an IR source: experiments using filtered beams from carbon arc must be regarded as less reliable due to the impossibility of accurate calibration before the filters are destroyed by heat.

The IR threshold doses are lower than the predominantly VL threshold doses, in the ratio of about 2:3. This can be accounted for by differences in spectral quality, skin reflectances and absorption. Calculations show that the energy absorbed between the skin surface and a depth of 2 mm. would be approximately the same in both series of burns.

Bearing in mind the area dependence of threshold doses per unit area for pain and first degree flash burns, the following may be regarded as best estimates available for threshold doses for 50% probability of various severities of flash-burning for young men.

		IRR (Source = 1000°C)		Predominantly VL Source about 5000°C	
Pain		0.7	cals/cm^2	(1.0)	cals/cm^2
1st degree flash burns		1.5	"	2.0	"
2nd degree flash burns:	Shallow	2.0	"	3.0	"
	Deep	(2.7)	"	4.0	"
3rd degree flash burns		(3.4)	"	5.0	"

The figures quoted in parentheses have not been confirmed by experiments with volunteers.

It is probable that these thresholds are higher (perhaps by 15%) than would obtain in a population including women and children.

It will be appreciated that all flash burns of 2nd degree or worse would be at a risk from infection and cause sufficient incapacitation to demand medical attention.

Numerous thermal experiments with animals have been made in the United States, usually with Chester White pigs. The skin of the latter has a similar response to thermal stimulus causing first and second degree burns, to that of human skin. Details of some of these experiments will be found in References (3) and (4).

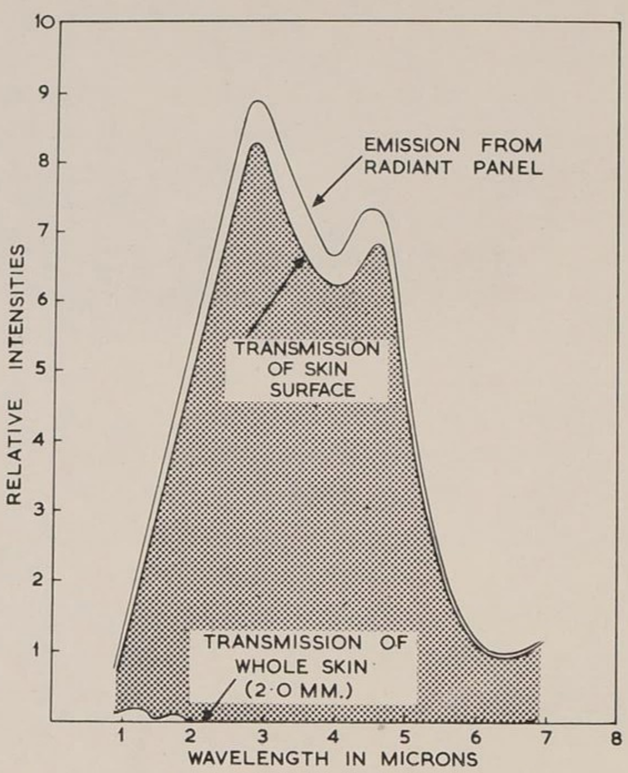
References

(1) Butterfield, W.J.H. et al. Flash Burns from Atomic Weapons. I. Observations on Flash-burning of Human Subjects in the Laboratory using Infra-red and Predominantly White Light Sources. Surg.Gyn.Obst. 1956. 103:655-665.

(2) Evans, E. I. et al. Flash Burn Studies on Human Volunteers. Surgery, 1955, 37:280.

(3) Perkins, J. B., Pearse, H. E., and Kingsley, H. D. Studies on Flash Burns: The Relation of the Time and Intensity of Applied Thermal Energy to the Severity of Burns. University of Rochester, New York. Atomic Energy Report UR-217, pp 4-58, December, 1952.

(4) Pearse, H. E., and Kingsley, H. D. "Thermal Burns from the Atomic Bomb", University of Rochester (N.Y.). Report U.R.254. (1953)



A. TRANSMISSION OF SKIN SURFACE BY INFRA RED RADIATION

FIGURES A AND B SHOW :-

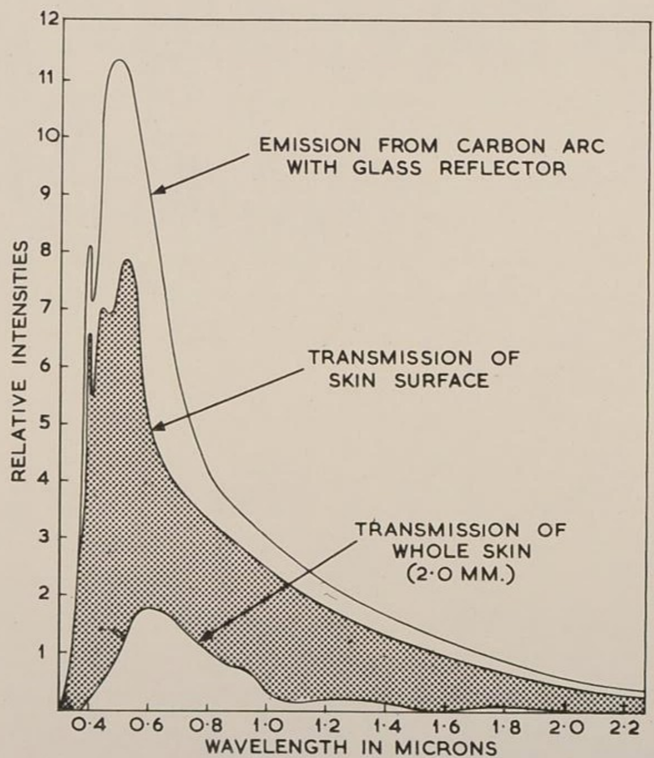
1. SPECTRAL DISTRIBUTION OF RADIATION FALLING ON THE SKIN FROM:-
   A. INFRA RED SOURCE
   B. WHITE LIGHT SOURCE

2. TRANSMISSION OF THE SKIN SURFACE.

3. PENETRATION BEYOND 2 MM. DEPTH INTO SKIN.

THE AREA BETWEEN TOP AND MIDDLE CURVES OF EACH FIGURE REPRESENTS SKIN REFLECTION.

THE SHADED AREA REPRESENTS ABSORPTION IN THE SKIN, FROM SURFACE TO 2 MM. DEPTH.



B. TRANSMISSION OF SKIN SURFACE BY RADIATION FROM PREDOMINANTLY WHITE LIGHT SOURCE

7.4 Healing Times of Uninfected Flash Burns

The information about threshold doses for flash burns given in Section 7.3. provides data for predicting for Civil Defence or military purposes the ranges of flash burns and the areas wherein they may be sustained (see Section 7.5). Another important factor in this connection is the duration of incapacitation to be expected if complications, especially infection, are prevented. This factor has been investigated methodically in the case of flash burns from predominantly white light (Method (ii) Section 7.3.2), between the limits of doses of 2.0 to 5.25 cals/cm^2. Above 5.25 cals/cm^2, the healing time will be affected by the surgical resources available to treat the 3rd degree burns caused. All the experimental flash burns were kept free from infection by suitable cleansing shortly after burning and by antibiotic barrier creams and occlusive dressings, and the course followed until they were accepted as healed by five qualified observers. The criteria for healing were absence of soreness to touch or firm healing of the skin over the burn. Soreness tended to outlast firm healing in shallower burns but it was taken as a criterion because flash burns are likely to affect the hands, and soreness there would incapacitate casualties.

The relationship between the dose of incident energy per sq.cm. and the healing time for the complete series of 1 cm. diameter flash burns from predominantly white light (unfiltered beam from carbon arc.), was:

$$t = 0.92\, q^2 + 1.26q - 4.26$$

where t = healing time in days

and q = dose in cals/cm^2.

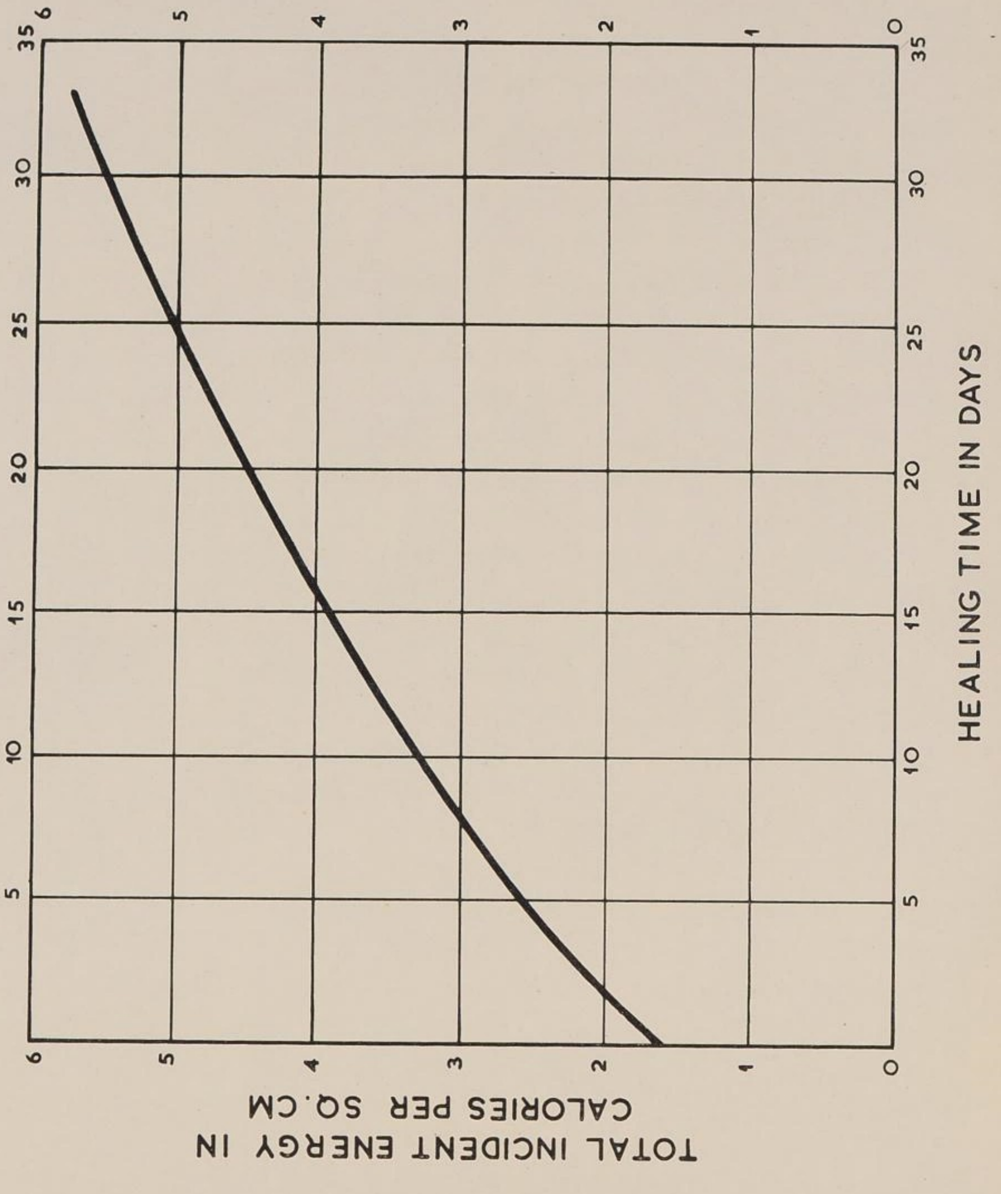
It may be noted that t becomes finite when q exceeds 1.5 cals/cm^2. When allowance is made for the area dependance of 1st degree flash burns, that the threshold is less if larger areas are exposed, it is apparent that the disability caused by 2.0 cals/cm^2 falling on the face or hand would be significant even if not warranting special medical dressings, etc. This relationship is given in graphical form in Figure 1 (from Reference (1)).

From the formula, the healing time to be expected for uninfected flash burns from 3.0, 4.0, and 5.0 cals/cm^2 of predominantly white light would be 8, 15 and 25 days respectively. These healing times would be extended by infection, which destroys the surviving skin cells thereby producing, in effect, a deeper burn. Thus, in another experiment, No. (i), Section 7.3.2, although uninfected burns healed in 12-24 days, one which was inadvertently infected required 42 days to heal.

Healing times were not studied systematically in the other investigations involving volunteers, but the qualitative statements given about healing times are in good agreement with the formula.

Reference

(1) Tripartite Conference on Effects of Atomic Weapons (1957). Paper AWEC/P(57)104 (Confidential). "Flash Burns from Atomic Weapons" by W. J. H. Butterfield and E. R. Drake-Seager.



HEALING TIME OF UNINFECTED
WHITE LIGHT FLASH BURNS
KILOTON WEAPONS

7.5. Casualty estimation

7.5.1 Flash burns

The hazard of flashburning can be estimated by calculating the threshold doses and healing times from the thermal doses received from surface of air burst atomic weapons.

The range of flash burning will increase with increasing weapon yield, and decrease with increasing atmospheric attenuation. The experimental results given in Section 7.3.2 should provide reliable data for weapons of yield up to 100 kilotons. The ranges so calculated can then be compared with those for gamma radiation injury and injury from the effects of the blast wave.

The importance of flashburning in a community can be judged best by considering the areas in which burns of various severities may arise, and by comparing these areas to those wherein other injuries may be sustained, always remembering that flashburning affects only those exposed directly to the heat flash, unshielded by buildings etc., which is by no means true of gamma and blast injuries.

The solutions to this problem for a 20 KT bomb exploded at a height of 2,000 ft. in weather with attenuation equivalent to a visibility of 12½ miles have been calculated and are presented in Table 1 below.

Table 1

Range and Area of Injury from Specified Effects

Cause of injury	Range of injury (yards)	Area of injury (Square miles)
Gamma radiation (150r)	1,450	2.1
Blast (2.7 p.s.i.)*	3,000	9.0
3rd degree flash burns (5.0 cals/cm^2)	3,200	10
2nd degree flash burns (3.0 cals/cm^2)	4,000	16
1st degree flash burns (2.0 cals/cm^2)	4,800	23

*This range depends on whether the population takes effective cover between the flash and the arrival of the blast wave. The estimate quoted is based on Japanese experience.

All things considered, the findings in Table 1 agreed well with the events observed in Japan.

The relationship between the range of risk of flash burns and weapon yield is given graphically in Figure 1. The ground area of the annulus for risk of flash burns is a function of weapon yield as given in Figure 2. Figure 3 gives an estimate of the relationship between weapon yield and minimum manpower loss for flash burns severe enough to demand medical attention. All three Figures are taken from Reference (1).

Some figures for the percentage of non-effectives among military personnel who receive second and third degree burns have been obtained from Reference (2), and are presented in Table 2. It should be emphasised that the data in Table 2 do not indicate the percentage of target population which becomes non-effective, but refer only to the percentage of non-effectives among those personnel who actually receive burns.

Table 2

Percentage of Non-Effectives* Among Military Personnel Who Receive 2nd and 3rd Degree Burns, as a Function of Time after Detonation

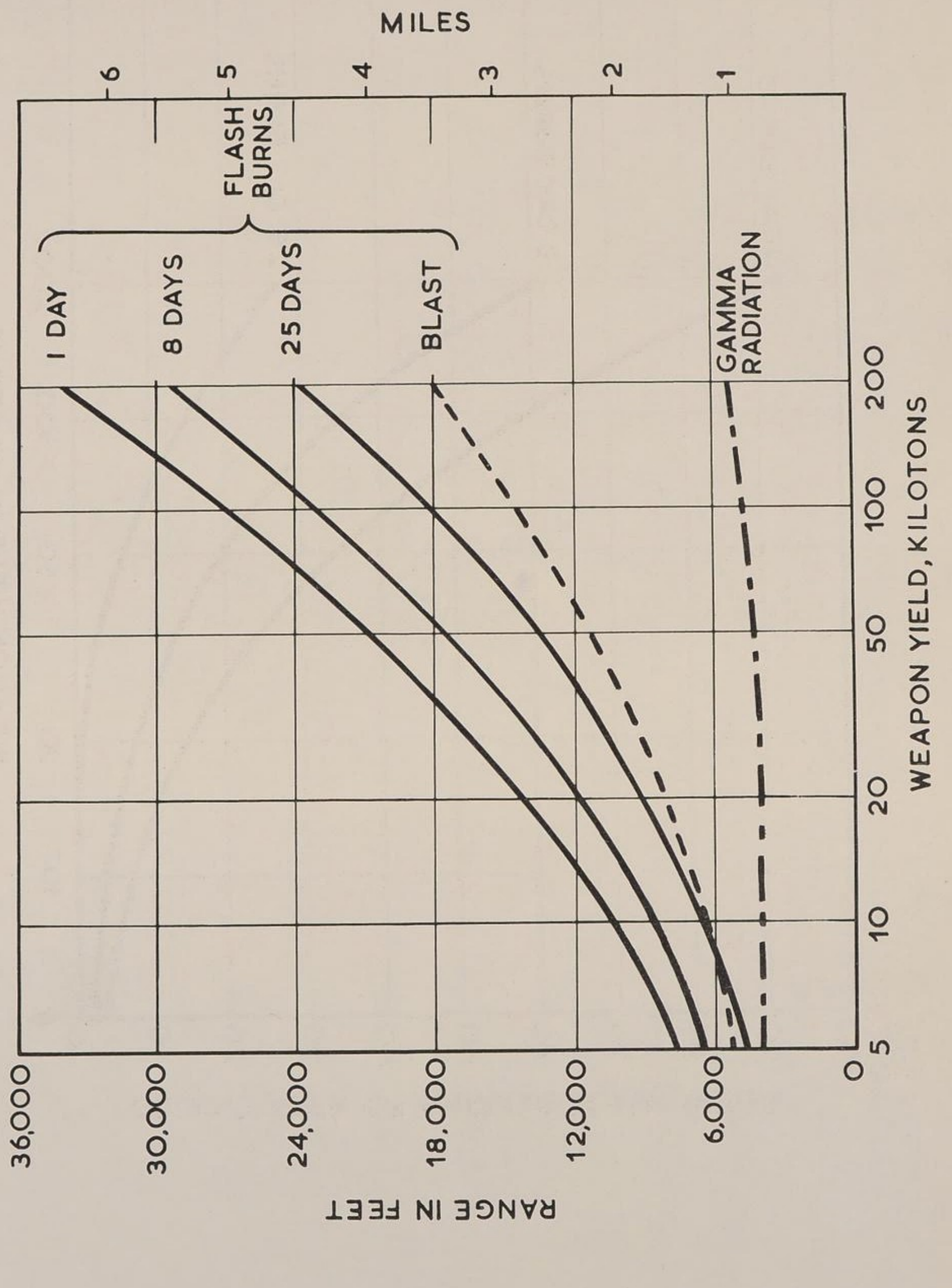
Hours after Detonation	Degree Area around both eyes burned		Degree Back of one hand burned		Degree 15% total body burned	
	2nd	3rd	2nd	3rd	2nd	3rd
0.5	10	50	8	60	10	50
1	20	100	10	30	0	55
2	40	100	30	30	0	55
3	50	100	40	30	0	55
4	60	100	50	30	5	60
5	80	100	50	40	30	80
6	100	100	50	50	50	90
24	100	100	100	100	80	100

*Note: A Non-Effective (or Combat ineffective) is defined as a person who, because of his injuries, is no longer capable of carrying out his assigned tasks. This is differentiated from the more common term "casualty" which means an individual whose injuries require medical attention.

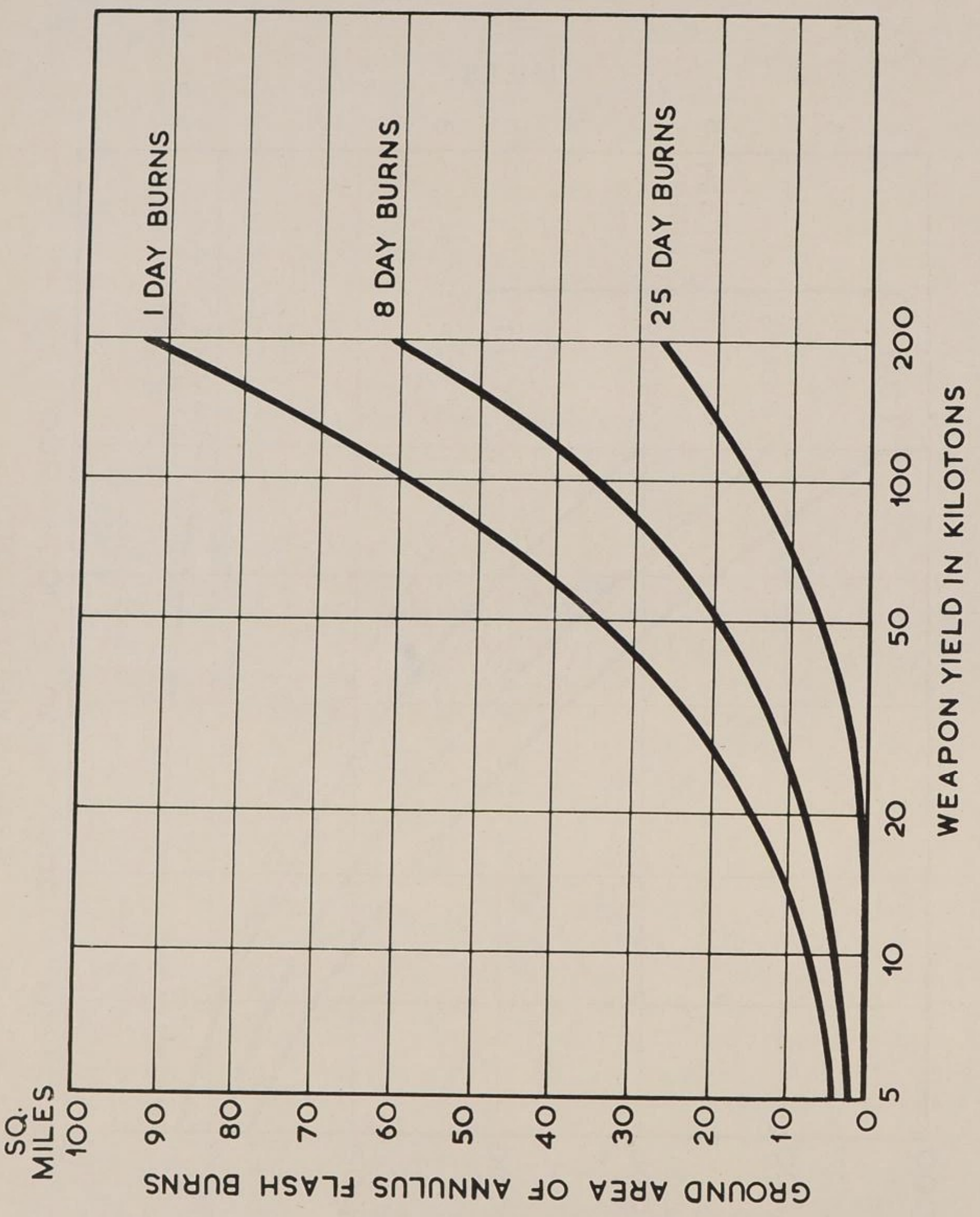
References.

(1) Tripartite Conference on the Effects of Atomic Weapons (1957) Paper AWEC/P9(57) 104 "Flash burns from atomic weapons" by W. J. H. Butterfield and E. R. Drake Seager (Confidential).

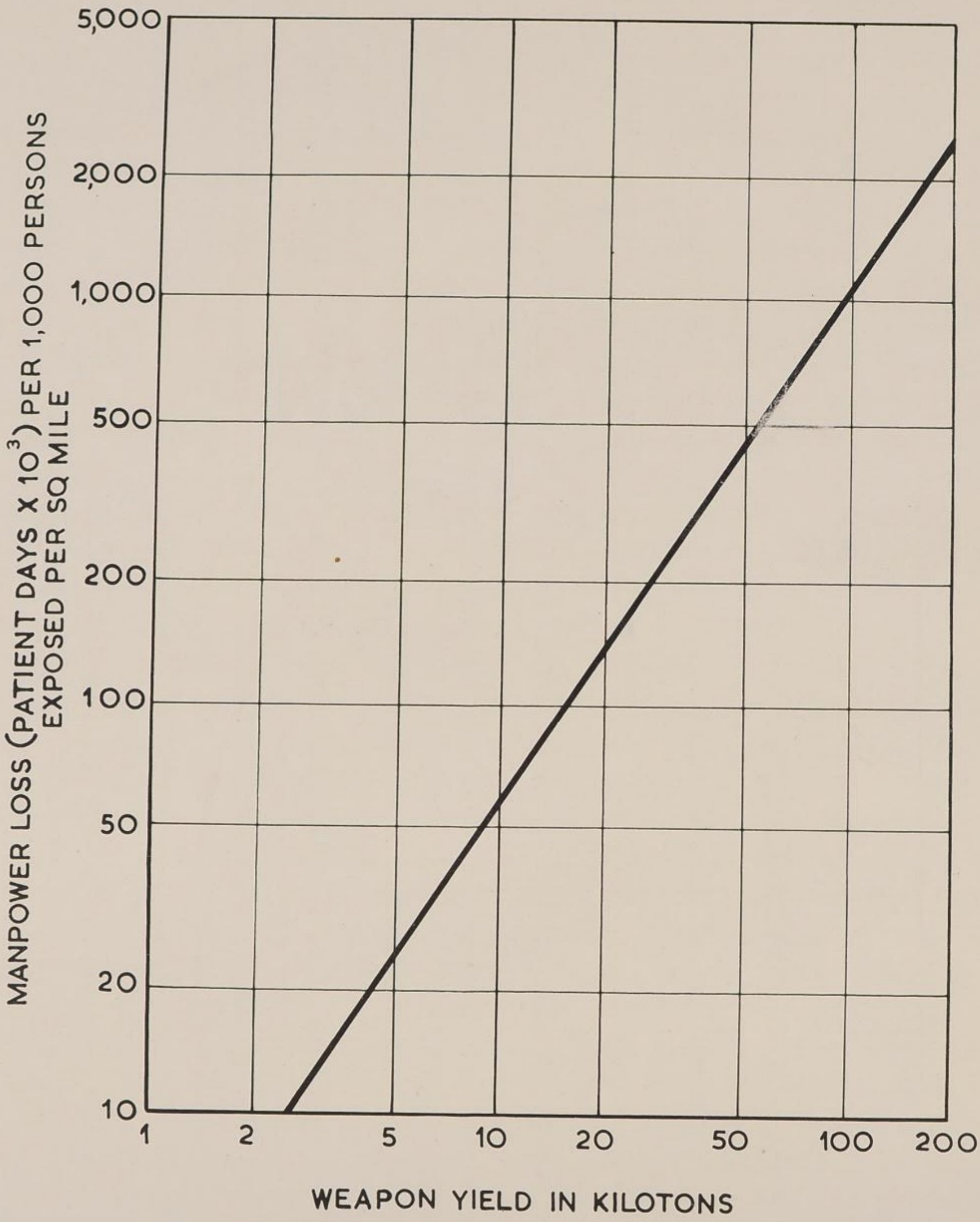
(2) Staff Officers' Field Manual - Atomic weapons employment. U.S. Dept. of the Army FM 101-31 (Secret Atomic).



RELATIONSHIP BETWEEN RANGE OF RISK OF FLASH BURNS AND WEAPON YIELD



RELATIONSHIP BETWEEN GROUND AREA OF ANNULUS FOR RISK OF UNCOMPLICATED FLASH BURNS AND WEAPON YIELD



MANPOWER LOSS FROM FLASH BURNS AS A FUNCTION OF WEAPON YIELD

7.5.2 Atmospheric Attenuation

In considering the effect of atmospheric attenuation on the range of flash-burning, it must be pointed out that atomic weapon tests have been conducted in remote places in good weather. It was assumed that the transmission of radiant heat under these circumstances would be good. It was further assumed that the transmission of radiant heat would be attenuated by the atmosphere in bad weather, with consequent shortening of the ranges of thermal effects. To calculate ranges in poor weather it was suggested that the transmission of thermal radiation be related directly to visibility. But visibility takes no account of infra-red transmission, nor does it allow for radiation scatter. Thus, while there is little doubt that rain or fog would severely curtail the transmission of the thermal radiation from an air burst weapon, there is evidence that the interaction of attenuation and scatter over the whole spectrum may mean that in dry weather transmission would, in effect, be roughly comparable to that previously quoted for a visibility of $12\frac{1}{2}$ miles, irrespective of the visibility appreciated by the human eye. (See also Chapter 1, Section 1.2.2).

7.5.3 Scaling Laws

The influence of weapon yield on the range, ground area and healing times of flash burns can be worked out by making calculations similar to those shown in Section 7.5.1 for different circumstances up to the limit of 100 KT bombs.

For larger weapons, the considerations become more complex. The duration of the flash becomes an important factor. The range of flash-burning cannot be estimated accurately until it is decided what period of time from the start of the flash should be allowed for casualties to take evasive action. Anyone who has volunteered for flash-burning experiments or focussed a burning glass upon his skin will know the quickness of the response to the painful stimulus of intense radiant heat. Although the physical measurements at trial explosions indicate that 70% of the total radiant heat from a 20 KT weapon is released in 0.5 seconds, the biological evidence from the Japanese survivors and subsequent animal experiments at weapon trials suggest that physiological responses, flash burns, were inflicted in a briefer period. Remarkable shadow effects were observed among the Japanese casualties moving at the moment of detonation. This discrepancy between biological effect and physical measurement has not been adequately explained.

It would seem unlikely that the population attacked would remain stationary for exposures of over 1.0 seconds while sustaining burns: they might not suffer pain during the first half of the exposure, but experience indicates that they would not keep still for the next half second after feeling stinging pain. If the flash continues for a longer period, the motion of the population trying to evade painful burning could bring them to expose again the area originally facing the fireball. Thus, although there has been considerable study of the change of threshold dose for 2nd degree flash burns of anaesthetised pigs for exposure times from 0.3 to 30 seconds, the formula derived* is hardly applicable to conscious man.

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* $Q_c = 3.73t^{0.224}$ where Q_c = Heat dose (total) cals/cm^2 and

t = time in seconds. See Reference (3) data sheet 6a.2.

Again, it has been shown that 4.8 cals/cm^2 given as a pulse simulating the heat flash from a 20-kiloton weapon and lasting 0.54 seconds, caused a 2nd to 3rd degree flash burn, whereas a pulse lasting 2.2 seconds caused a superficial 2nd degree flash burn, and a pulse lasting 3.4 seconds caused only a 1st degree flash burn in man. However, before assuming that an extension of the duration of the heat flash by a factor of nearly 7 (0.54 to 3.4 seconds) would approximately halve its burning effect, it must be noted that the pulses were achieved by slowing the venetian-blind mechanism used, i.e. the longer pulses were not designed to simulate the heat flash from large weapons.

The information in Table 1 below, on the thermal doses causing burns to bare skin for various weapon yields, has been obtained from References (1) and (2). Some results with animals are quoted in Reference (3). A graph showing critical radiant exposures for first and second degree burns to bare skin, as a function of weapon yield, has been given in Figure 1 of Section 7.3.1. Attention is also drawn to the Target Damage Charts given in Part I. In using these data for the estimation of burns from high yield weapons the limitations discussed above should be kept in mind.

Table 1

Damage Criteria for Burns to Bare Skin (cals/cm^2)

	Weapon Yield		
	1 KT	100 KT	10 MT
1st degree	2	2.7	3.5
2nd degree	4	5.5	7
3rd degree	6	8	11

References

(1) Staff Officers Field Manual - Atomic Weapons Employment. U.S.Dept. of the Army FM 101-31 (1956) p.71. (Secret Atomic)

(2) Capabilities of Atomic Weapons - U.S. Dept. of the Army, FM 23-200 (1957) p.6-14 (Confidential)

(3) The Thermal Data Handbook. A.F.S.W.P. - 700. Sanitized Edition. 1954. (Confidential).

7.6 Diagnosis and Treatment of Flash Burns

7.6.1 Diagnosis

The recognition of the parchment-like skin, denuded of hairs by singeing, in severe (3rd degree) flash burns, presents no problems once the skin has been cleansed. In more severe burns the skin may be charred. The vivid reddening of slight (1st degree) flash burns is easily recognised. Brief mention must however, be made of the possible errors from hasty diagnosis in blister (2nd degree) flash burns. In the early stages, these injuries show vivid erythema, and if seen less than an hour after infliction no oedema would be discernible. This means that blistering may have to be suspected in all 1st degree burns seen immediately after an attack, with consequent administrative problems. After one hour, or perhaps longer in cold environments where the development of local changes may be delayed by the coolness of the skin, the presence of oedema (swelling) in the burned area must be taken as presumptive evidence that blistering will occur later, so that such cases were better treated to exclude infection.

7.6.2 Treatment

It is now widely recognised by the medical profession that the treatment of flash burns after atomic explosions presents several important features. History has shown that the proper hospital treatment of one hundred or so severely burned casualties presents the medical services, even in peace conditions, with a particularly heavy burden. It has been shown in Section 7.5 that the number of such flash burn casualties after an atomic bomb attack would be very large, especially if the community were not warned, or did not heed warning. It can be calculated from the formula for healing times quoted earlier that the minimum economic burden from 2nd and 3rd degree flash burns after the explosion of the nominal atomic bomb under the circumstances mentioned earlier would be 52,000 man-days per 1,000 persons flash-burned. Simple extensions of this calculation also show that unless such cases were treated, the complications of infection and scarring would result in even heavier long-term burdens on the community as a result of neglect. As a conservative estimate, the previous figure for man-days lost would be raised in the absence of treatment by a factor of 3. Thus treatment under the circumstances considered would save about 100,000 man-days per 1,000 persons flash-burned. The gains from mass treatment are therefore clear. The object of mass treatment would be to provide, as far as possible, the following benefits to each casualty needing one or more of them.

(a) Local treatment - Specific - There is no known specific local treatment for flash burns. Impressed by the possibility that the slow progression of events in shallow blister-burns might be due to noxious substances diffusing downwards from the superficial layers of the skin, Butterfield investigated various measures which might interfere with the process. None of the remedies he tried altered the sequence of events in the burned area.

(b) Local treatment - Early preventative - As a general rule, any flash burn showing blistering or blanching of the skin will require treatment to prevent local infection. The exact methods used to exclude infection from the flash burn will obviously depend upon the resources available, the judgment of the medical attendant, and the man-power available to effect therapy.

(c) General treatment - Early - In those cases where (2nd or 3rd degree) flash-burning is extensive, or where other burning injuries complicate flash-burning so that the total burned area is extensive, means should be found to combat circulation changes by restoring the circulating blood volume. This may be done by oral fluids, e.g. slightly salt water or in larger burns by intravenous therapy. Again, many exigencies will dictate the treatment given.

(d) Local treatment - Late - In the case of extensive 3rd degree flash burns, or 2nd degree flash burns which have deteriorated to a similar depth of injury through infection, plastic surgery will be required to restore adequate function. This may be followed by rehabilitation, exercises etc., later.

(e) General treatment - Late - Those flash burn casualties who require more than a single plastic surgical operation to repair their wounds will almost certainly require extra supportive therapy - special diets and blood transfusions.

7.7 The Prevention of Flash Burns

The methods of reducing flash-burning risks if atomic or thermonuclear warfare seemed imminent may be summarised as follows:-

(a) Dispersion of the population in space and time - Flash-burning is a daytime and especially a "rush-hour" hazard. Any policy designed to reduce the number of persons likely to be outdoors exposed to attack from moment to moment would reduce the risk to the community as a whole.

(b) Warning - Sufficient warning might be given to permit all but essential personnel to seek cover or air raid shelters. This might be difficult for armed forces in the field. With civilian communities, the problem would be that, in the presence of weapons of mass destruction, all warnings would have to be heeded. This would obviously raise serious problems of production and questions of strategy.

(c) Personal protection - For those whose duties placed them out of doors in a position of risk, or for all citizens in the event of a breakdown of warning vigilance, suitable clothing, covering as much of the skin as possible would offer protection. This would be of special importance if it could shield the face, ears and hands, and the legs in women and children. In this connection, it is important to bear in mind that multiple layers of clothing greatly enhance protection, that light colouring enhances protection, but that some fabrics are inflammable and therefore highly unsuitable in such circumstances. A detailed discussion of the protection afforded by clothing is given in Chapter 8.

7.8 The Ocular Hazard from a Nuclear Explosion

Introduction

The maximum dazzle effect produced by a nuclear detonation is sustained when the fireball is seen directly, that is when its image is formed on the retina. In this - the most severe case - the brightness of the source does not vary inversely as the square of the distance when atmospheric attenuation is neglected, for, although at greater distance less light is received by the retina, yet it is concentrated in a smaller retinal image which therefore maintains the same brightness irrespective of distance. The dazzle effect produced by reflected light from cloud or from other highly reflecting surfaces such as snow is affected by distance, since the light reflected by these surfaces is a factor of the light incident on them, and this varies inversely as the square of the distance of these surfaces from the source.

The effects on the retina produced by a nuclear detonation differ from those on the skin surface by virtue of the blink reflex, which acts like a shutter in front of the retina and can therefore prevent it from receiving the high intensity light for the entire duration of the explosion cycle. The exposure received by the eyes thus depends on whether the eyes have blinked and whether, having blinked, they have reopened to look again at the fireball.

The effect produced by the stimulus is therefore caused to vary, but even if the stimulus were constant and known, a number of other variables would have to be taken into account. The most fundamental of these is related to the subject's task. How much dazzle can he tolerate? At night does he require night vision, and if so how much? Has he merely to observe instruments which can be floodlit to a required level if he is dazzled? What part of his visual field is exposed to the dazzle source - his fovea or the peripheral visual field? Were his eyes moving when the flash of light was received? Was the flash received by both eyes in corresponding points of the retinae? What is the nature of his task: is it one of legibility of instrument markings, or is it from perception? What is the probability of being dazzled anyway?

These are some of the variables which have to be considered in assessing the effects upon vision of an unexpected nuclear explosion, and it will be obvious that to provide reasonably accurate quantitative data as to the effects produced in all situations is quite outside the scope of this manual.

The following section however attempts to give the reader the necessary background so that he may be able to form some judgment as to the severity of dazzle likely to be sustained. Towards this end, graphs are provided from which the expected luminance can be assessed and from which one can calculate dazzle recovery times to enable one to see a specified test at a given illumination. The reader should then be able to assess whether in the problem he is considering, the visual effects are likely to be above or below this known value.

The data which will be provided are based partly on theory, and partly on experimental work in which measurements were made of the dazzle produced by looking at a nuclear explosion without any protection other than that given by an exposure which was timed to last 1/10th second from the start of detonation.

Degree of Retinal Damage

As already pointed out, if atmospheric attenuation is neglected then retinal burns and dazzle, which are both dependent upon the optical system of the eye, are affected by distance only in that the area of retina involved becomes smaller as distance from the explosion centre increases. Only when the resolving power of the retinal mosaic is reached does the apparent brightness of the source decrease with increasing distance. It is then physiologically a point source.

There is ample evidence that retinal burns can be produced by nuclear explosions just as similar burns can be produced when the sun is observed for too long as, for example, during a solar eclipse. In the later stages of healing, a severe burn may be associated with such complications as retinal detachment, but its immediate tactical importance is that the subject will have a permanent blind spot equal in size to the burnt area. If the burn is other than in the line of sight, it may, depending upon its size, cause only slight impairment of ability to complete a task. Even in the line of sight however it may still be possible to read instruments if the area involved is less than 2°.

Since there are categories of slight retinal damage which can also be classed as severe dazzle, the operational problems posed by retinal burns and by dazzle must be regarded as one, the problems associated with retinal burns being merely an extreme form of those associated with dazzle.

If a severe retinal stimulus should be received, the chances of successful completion of a mission and of return to base may well depend upon training, for as the stimulus severity increases so the results of that stimulus cause more stress. Consequently a visual task which may be completed satisfactorily in a laboratory, may, in the field, become too difficult as the visual stress summates with the other stresses of the task. Training not to look at the detonation after a blink; shutters to improve upon the blink reaction time should an explosion take place near or in very clear air; if necessary, transparencies to enable the wearer to see instruments by the reflected light from clouds and yet not be dazzled: these are some of the protective measures, but training is by far the most important because under certain conditions protective devices may fail. The dazzle from clouds calls for similar measures, but the effects will be small compared with the effects produced by the image of the fireball on the retina. Whilst this light from clouds in a night explosion constitutes a major problem to the maintenance of near maximal dark adaptation, this is more of a problem for ground troops than for aircrew whose present duties do not require of them such a high degree of dark adaptation. It is to this question of degree of night vision required that one must attribute the main differences in opinions which have been expressed with regard to the severity of this problem.

Luminance

Since the brightness of the fireball varies with the temperature of the two pulses, one refers to integrated luminance, which is usually considered as being from 10^{-4} seconds (when the fireball is still subtending a very small angle at the eye) to 100 milliseconds (which is about the fastest possible blink reaction time). Fig. 1 shows the luminance calculated on the basis of the temperature for a fireball from a 20KT explosion. From this one can calculate and measure the integrated luminance for explosions of different yields by scaling the time axis by $W^{\frac{1}{2}}$ (where W = yield in kilotons). Thus for a 10 KT explosion the time scaling factor which has to be applied to Fig. 1

$$= \frac{10^{\frac{1}{2}}}{20^{\frac{1}{2}}} = 0.707$$

Since the luminance/time curve is on a logarithmic scale, this scaling merely results in displacing the curve to one side or the other. The integrated luminance for different yields is shown in Fig. 2. This was calculated as shown above, and refers to the integrated brightness within the period of 10^{-4} to 10^{-1} seconds.

Blink Reaction Times

The reason for considering integrated luminance up to 100 milliseconds is that this is approximately the duration of the fastest blink reaction time. Studies carried out by Cobb and Sears (Ref. 1) show that about 40 milliseconds after a light has been switched on, there can be detected in the electromyogram, the activity which accompanies the initiation of lid closure. This closure however does not occlude the pupil completely until 100-200 milliseconds after the flash.

Irving (Ref. 4) has found the reaction time to complete occlusion of the pupil by the lid is of the order of 100-150 milliseconds. He has found that the shorter times are associated with stimuli nearer to the fovea as well as with higher intensity stimuli. Thus the reaction time is dependent to some extent on the intensity of the perceived stimulus. As indicated by Cobb and Sears however, the stimulus need not be one of light, for any stimulus can give rise to a blink response. They suggest that the nervous pathway may be cortical and indeed one finds that the blink reflex is amenable to training. Thus a subject can either be trained not to blink when a flash appears or he can be trained to blink and to keep his eyes closed. Training in this connection consisted of verbal instruction and experience. The blink reflex associated with corneal stimulation is however unaffected by training and probably involves lower pathways mediated through the long ciliary nerves from which the cornea receives its nerve supply.

Dazzle

Fig.3, which illustrates the results of experiments, shows the recovery times after flashes by various amounts of light, all of which were delivered to the eye within 2 seconds (Ref. 7). It is possible to verify the shape of this curve by comparing the results obtained by different workers. Although recovery times measured are not necessarily to the same threshold and although different workers employed different criteria such as absolute threshold, form or legibility, these differences introduce a factor which can be considered as constant for each experiment.

The curve marked BHC was obtained by Crawford (Ref. 2), employing flashes of different durations on the fovea, and shows recovery times to 0.14 ft/L. Although his test object was similar to that employed in experiments CS and CI he shows longer recovery times. The data marked U.S. were obtained by Metcalf and Horn (Ref. 5) by looking at the carbons of a searchlight. Their recovery times refer to a threshold of 0.07 ft/L. The curve marked CS was obtained with a tungsten source, whilst point CI was obtained by observing a nuclear explosion (Ref. 9). It can be seen that the curves for each of these reports lie parallel to the curve obtained with the data of the sun experiments (Ref. 7 FPRC.787). It seems reasonable, therefore, to accept the form of this curve as representative of changes in recovery time.

In dealing with the problems of detecting a small square of light of luminance 0.14 ft/L against a black background, it is preferable to use the curve CS-CI for which this task was the specific endpoint. A task involving legibility of lettering will be more difficult and therefore will require slightly longer recovery time, whilst the task involving form perception (if the form subtends a large area) will require a shorter recovery time.

Thus from Figs. 2 and 3 it can be seen that without atmospheric attenuation a 10 KT bomb will in the first 100 milliseconds produce so much dazzle that it will take some 200-300 seconds to see against a black background a source of luminance of 0.14 ft/L, providing the flash has fallen on the fovea. If the explosion is greater than 20 KT, temporary retinal damage will begin to take place.

When considering atmospheric attenuation one would expect less damage in the form of either dazzle or retinal burns to be sustained when witnessing a detonation in the megaton range, for if one were sufficiently far from the detonation not to be seriously endangered by skin burns or by blast, the intervening atmosphere would probably attenuate the luminance to a safe level provided the exposure lasted only 100 milliseconds. To obtain a more accurate assessment of dazzle however, atmospheric attenuation must be taken into account. For this purpose Table 1 below gives the attenuation coefficient of air as a function of horizontal visibility range.

TABLE 1

Visibility (Km)	Attenuation Coefficient (σ)
2	1.2
4	0.98
8	0.5
15	0.268
30	0.132
60	0.066

Consider for example a bomb of 500 KT whose detonation is observed for 100 milliseconds from a distance of 20 Km. when the visibility is 25 Km. (daylight conditions and therefore a pupil diameter of about 4 mm. maximum). What will the luminance be when integrated over the 100 milliseconds period, and how long will it take the observer to recover so that he may see a small square of luminance 0.14 ft/L in darkness and with a natural pupil?

The atmospheric transmission in the visible range = $e^{-\sigma d}$ From Table 1

$\sigma = 0.16$ for 25 Km visibility. d = 20 Km, so the

$$\text{transmission} \quad \frac{1}{e^{.16 \times 20}} = 0.041$$

From Fig. 2, a 500 KT explosion gives in the first 100 milliseconds, an integrated luminance of 220,000 $c/cm^2/sec$. With atmospheric attenuation this becomes 220,000 x 0.041 = 9,000 $c/cm^2/sec$.

From Fig. 3 this amount of light is associated with a recovery time of 100 secs. before a test object of luminance 0.14 ft/L becomes visible through the after image.

Pupil Size

The extent of pupillary dilatation in darkness is often over estimated. There is furthermore, continuous movement of the pupil not only in response to light and shade, but in response to emotional changes, and in general, in response to variations in balance between the ortho and para-sympathetic nervous systems. Variations in accommodation as one looks from near to far also affect pupil size. One can, however, make a reasonable approximation and say that by night conditions the pupil is twice as wide as it is by day conditions (8 mm. and 4 mm. respectively). Thus in Fig. 3, which was for flashes delivered to a daytime pupil, the total stimulating light would have to be multiplied by a factor of 4 if one considers a flash taking place at night, when the subject is also in darkness.

Thus, for example, the 9,000 c/cm^2/sec. calculated above would now be regarded as 36,000 c/cm^2/sec. and the recovery times would therefore according to Fig. 3, become about 300 seconds instead of 100 seconds for the daylight case.

The problem however is not so great, because, if one considers the retinal directional effect of Stiles and Crawford it will be found when the diameter is increased from 4 mm to 8 mm, the effective area of the pupil is not increased from 12 mm^2 to 48 mm^2 but only from 10 mm^2 to 24 mm^2 - an increase of 1.5 times instead of 4.

Probability of Sustaining a Flash on the Fovea

In considering the effect of a very bright extended source whose centre is at various distances from the fovea, it is found that as soon as the edge of the image begins to fall outside the fovea, the recovery times will rapidly decrease to values which are dependent on the amount of intraocular scatter, of atmospheric scatter, or of diffuse reflection from neighbouring reflectors such as clouds.

From one aspect, this is an oversimplification of the problem and recovery times may not in fact decrease as rapidly as the flash goes "off centre" because the scatter and diffuse reflection will be proportional to the luminance of the source. From another aspect however, recovery times may decrease more rapidly than has been suggested, because although foveal vision has here been considered as a point, it is in practice accepted as comprising an area which subtends 3°. Consequently if part of the fovea is left unstimulated, it is still possible to read with little difficulty.

Since there are such differences in the effect on foveal vision produced by a flash taking place directly in the line of sight, compared with one taking place on the periphery, and since the fovea subtends such a small portion of the whole visual field, it is clearly of importance to determine the probability (P) of a flash taking place directly in the line of sight.

Consider a flash occurring in random positions in search fields of different sizes. Different diameters of flash source will be considered, also a fovea in which maximal dazzle takes place only when some part of the image of a circular fireball overlaps on to the central 1°. It is believed that accepting a 1° field instead of an overlap on to the centre of the fovea, as has been found experimentally permissible, will weight the P values so as to compensate for the failure to consider scatter of light.

If the flash source is represented as a point in random positions, the probability of it falling in the 1° foveal field will be in the percentage which the area of the foveal field bears to that of the search field. As the flash is an extended source this fact can be taken into account by increasing the size of the foveal field to $(1 + d)^{\circ}$ where d is the angular diameter of the extended source. When the size of search field is 4π steradians the flash may come from any direction; (the unrestricted binocular field has been estimated to be 1.5π steradians). The results of these calculations are seen in Fig. 4. It is evident, even when considering a small search field subtending a plane angle of 40°, in which the observer knows the explosion will occur, that the likelihood of the flash taking place in direct line of sight is very small, even considering a source which is very large or very near.

This purely mathematical assessment of the risk has been purposely weighted on the side of safety, and in fact the probability of being dazzled by a fireball is less than that which has been suggested, because the maximal effects of dazzle will be sustained if the edge of the fireball comes onto the centre of the fovea and not as has been assumed in this case on the central one degree area.

Eye Movement

In this assessment of the risk no account has yet been taken of eye movements, some of which are so rapid that the image of the distant fireball will be on the retina for only a very short time. According to Westheimer (Ref. 6) some saccadic movements of the eye are as fast as $500\text{-}550^{\circ}$/second. An indication of the effect of such fast movements upon the retinal exposure time to a small source may be obtained by considering a source of 3° angular size and an eye movement of 600°/second. This source will travel its own diameter on the retina in 5 milliseconds and each retinal element in its track would therefore be maximally stimulated for only 5 milliseconds. From experimental work it is known that this exposure would not result in serious dazzle.

In addition to these saccadic movements there are slower movements which are normally present during fixation. When the eye is attempting to fixate in darkness, Ditchburn and Ginsborg (Ref. 3) assess that these involuntary movements are increased by four times in amplitude. This would mean that even during attempted fixation in a dark sky, involuntary eye movements of $\frac{1}{2}^{\circ} - 1^{\circ}$ would be taking place. It is probable that the same amount of involuntary movement would take place when fixation is attempted whilst looking at a bright and empty visual field such as a cloudless sky.

Protective Measures

Training. Two methods of protection are training, and a mechanical shutter. If the mechanical shutter should fail, then recourse will have to be made to training. If a transparent shutter is employed the wearer will again require to be trained. He will have to be instructed not to look at the fireball even through the transparency, because if the fireball lasts for a sufficiently long time he may sustain a burn of the retina just as a retinal burn may be sustained when observing a solar eclipse for too long through a filter which is not sufficiently dense. In this connection the yield of the weapon must be taken into account, since the duration of the explosion depends on the yield. Only with an opaque

shutter will it be possible to eliminate training and then only if the shutter is entirely dependable. It seems unlikely that such a device will be produced because a sensing element operating on flux emitted or on rate of rise of radiation may fail to be triggered by a source which is too far away. That source however may still give rise to a retinal burn if it is looked at.

Training therefore is the first essential in protection from the ocular hazard associated with a nuclear explosion. The training should consist of instruction on the advantage of looking away from a high intensity light source should one appear without warning; on the very low probability of a flash falling directly on the fovea; on the protection afforded by the blink reaction time of between 0.1 and 0.2 seconds, provided the subject does not reopen the eyes and look at the source; it should be pointed out too that the most likely danger is not from a burn of the retina but from dazzle produced by the light scattered by clouds and the atmosphere. This dazzle whilst lasting a long time if one requires to re-adapt to low thresholds need interfere with visibility of instruments only for a few seconds if these have been illuminated by white flood-lighting to a luminance of instrument marking of about 5 foot lamberts or above (Reference 7).

The use of a simulator to give an impression of the angle subtended by a fireball of different yields and at different distances might with advantage be combined with a high intensity light source which could provide a source of calculated dazzle. The effect upon aircrew performance might be demonstrated by giving a flash on the fovea whilst the subject is "flying" an aircraft simulator under simulated night conditions.

Shutter

Whilst more protection may be derived from an opaque shutter, if this device remains over the eyes for the duration of the explosion the pilot who is subject to the effects of a weapon in the megaton range may be blinded for half a minute - not by the dazzle but by the protective shutter over his eyes. It seems therefore that one must have a transparent shutter which at least would enable the wearer to see his instruments should the cabin be illuminated by intense light from the explosion. The transparent shutter would therefore protect principally from dazzle by reflected light, but as already indicated, the subject would still have to be trained not to look directly at the fireball, otherwise his dazzle will be more severe and he may in addition sustain a retinal burn. The filter suggested for such a device is one of neutral density and of 10%-15% transmission which would allow it to be employed also as a sun visor.

Since the eye can look at the fireball directly for as long as 100 milliseconds depending on distance, attenuation, and yield, a shutter need not close in a very short time, and this simplifies the mechanism involved. Thus the difficulties associated with opaque shutters and instrument visibility, could now be solved by a shutter over the canopy. A roller blind type of shutter might be the simplest protective device if it were combined with white flood lighting of instruments.

To the list of protective devices given in Reference 8 should be added the electro-mechanical shutter which has been developed by the United States Air Force. This device consists of two superimposed graticules which when moved by a very small amount render the whole field opaque. The movement is produced by detonation of a small cartridge

which in turn is triggered by a light sensing element. This device has been reported to operate in less than a millisecond. The other device which should be mentioned is a photochromic substance being developed by the National Cash Register Co., in U.S.A. They have produced a substance which, dissolved in various media, changes under the action of light from transparent to dense in a few milliseconds. The process is reversible and when the light is removed the substances becomes transparent again either with equal speed or in several hours depending upon the medium in which it is dissolved. It is claimed that it may be possible to achieve a filter of density 3 by this means, but at present the problems faced are the method of applying this device to goggles in the form of gelatin or to a visor in the form of a fluid sandwich. The sensing element employed with such shutters is usually activated by the intensity of light falling on it. A large distant explosion may therefore fail to a trigger a sensing element which would be triggered by a small explosion at close range or by a large distant explosion in very clear air.

The time in which the shutter has to close must be dictated by such factors as size of the explosion and distance beyond which protection is required, these factors themselves being dictated by the limits beyond which the subject may be expected to survive the effect of blast and thermal radiation.

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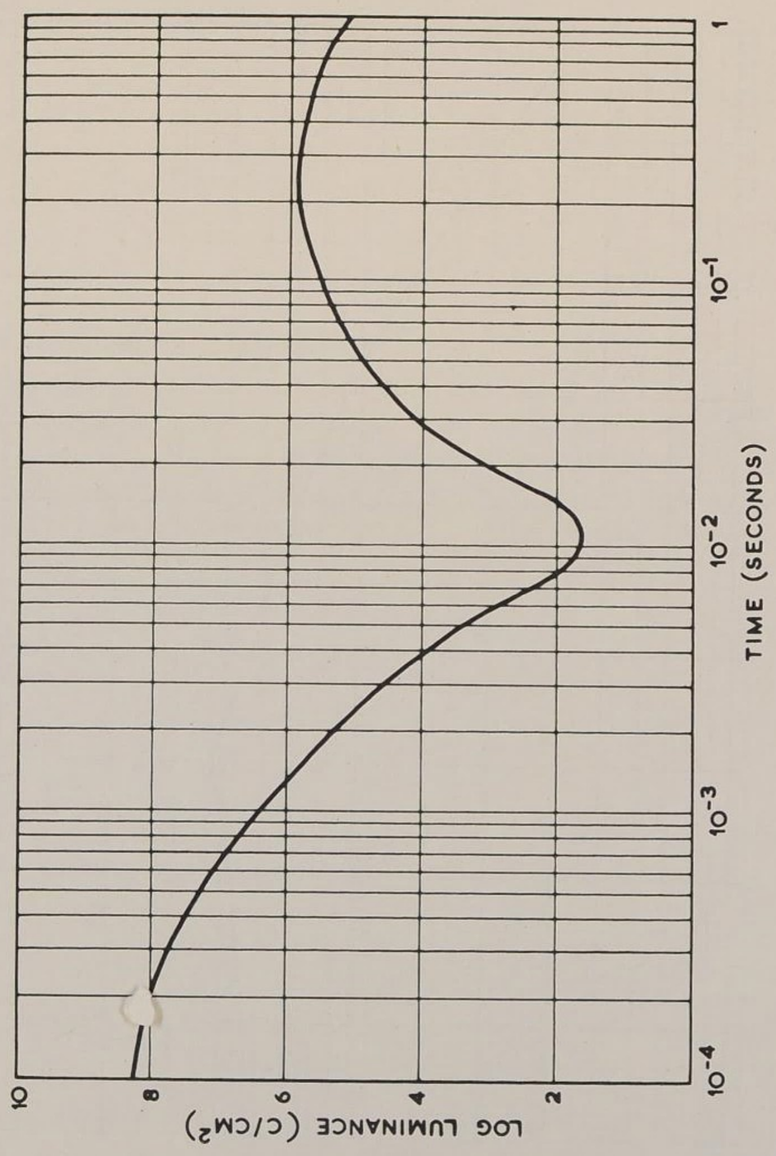
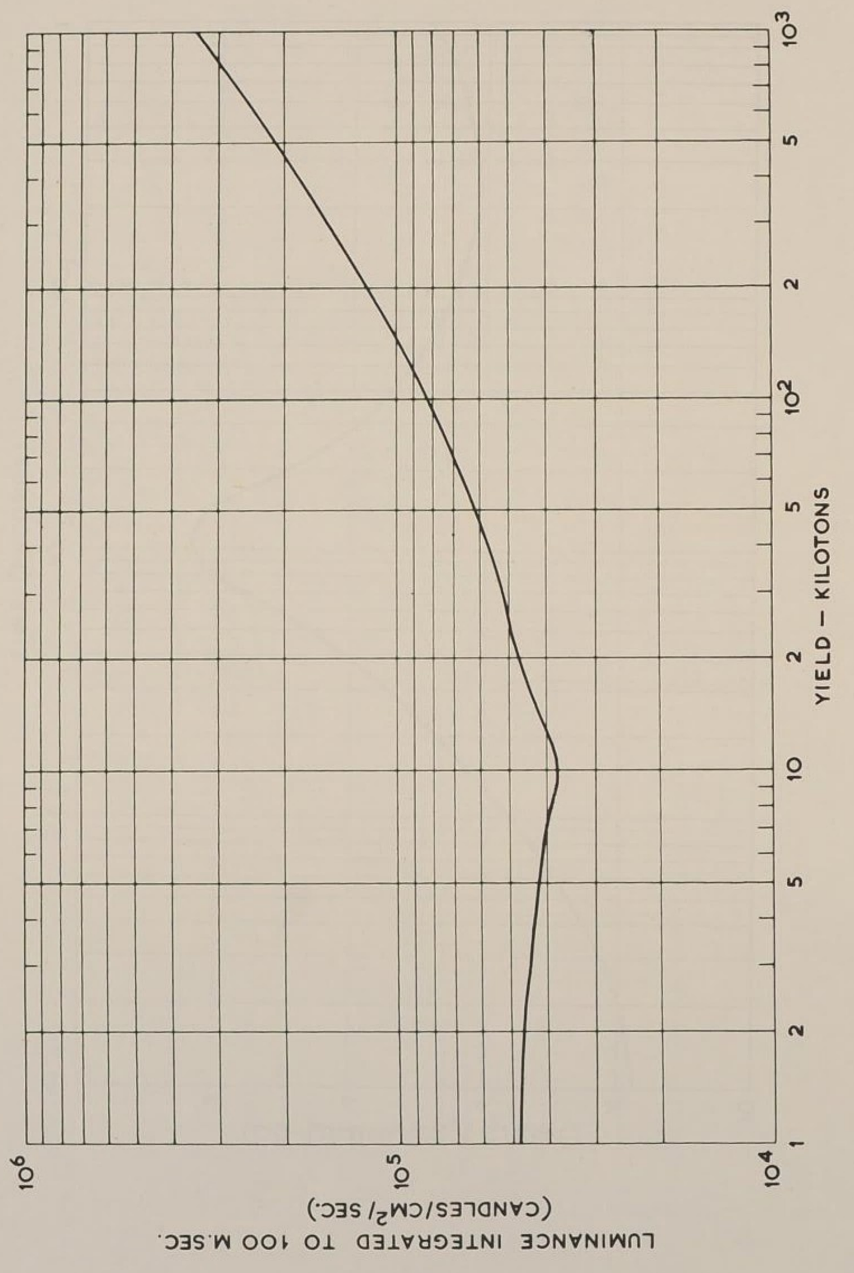


LUMINANCE OF FIREBALL
DERIVED FROM TEMPERATURE

PART VI
CHAPTER 7
SECTION 7·8
FIGURE 2

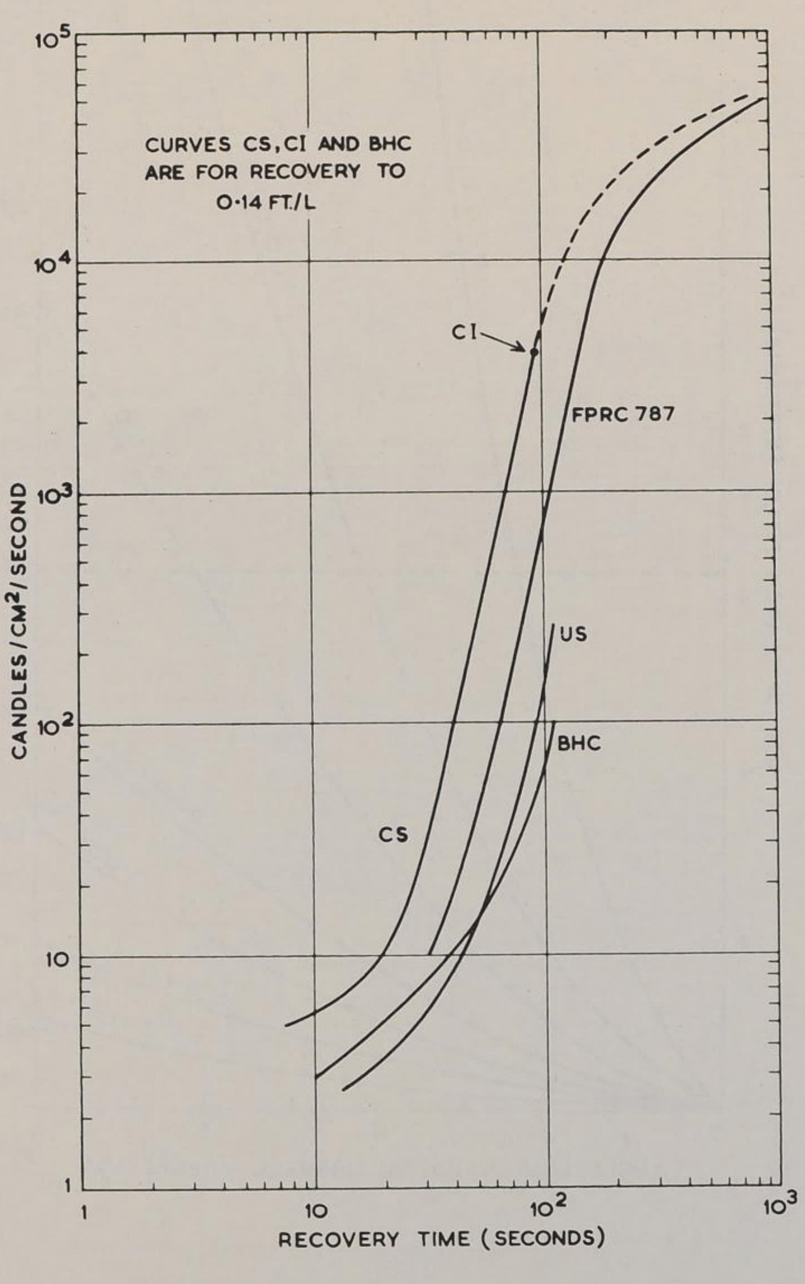
D1/57
NOV. 1959

CONFIDENTIAL



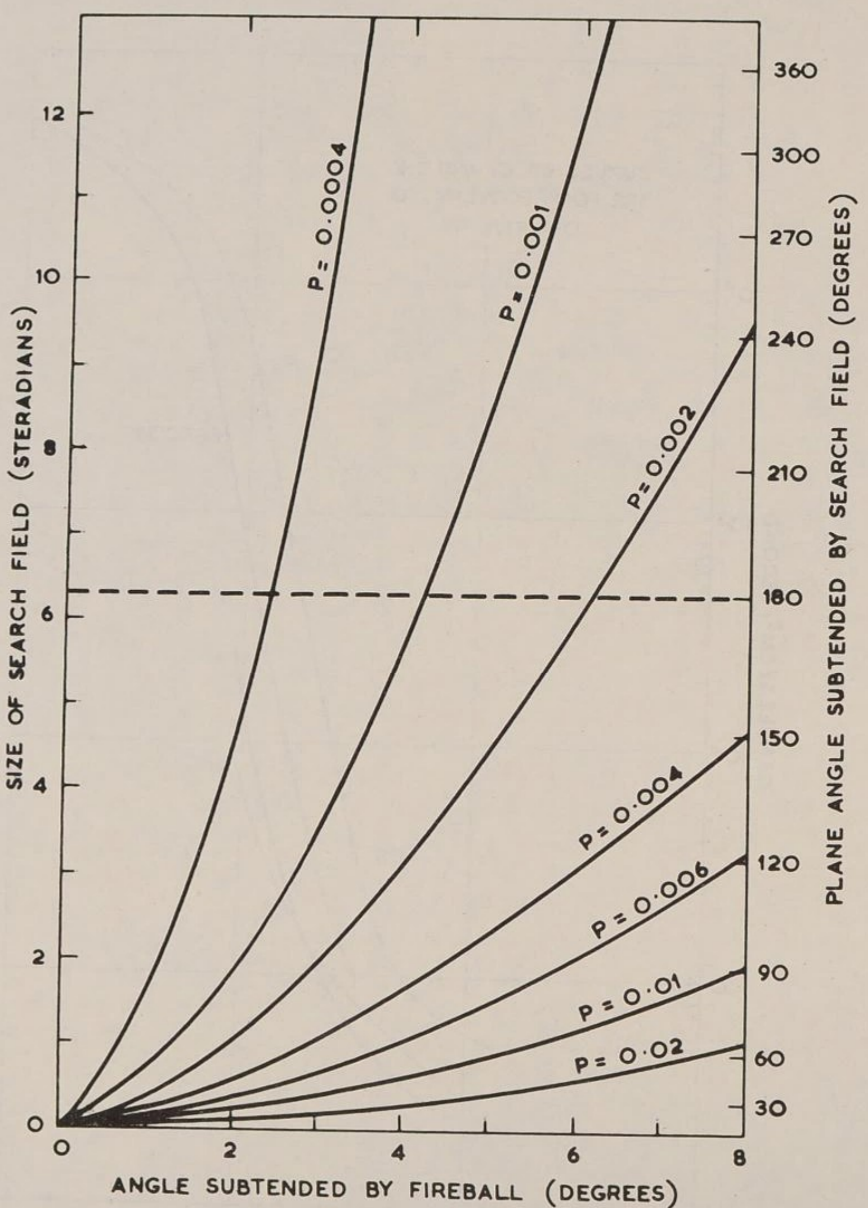
VARIATION OF INTEGRATED LUMINANCE WITH YIELD
(NO ATMOSPHERIC ATTENUATION)

CONFIDENTIAL



COMPARISON OF RECOVERY TIMES

CONFIDENTIAL



PROBABILITY OF AN IMAGE OF A FIREBALL FALLING WITHIN THE CENTRAL 1° OF THE FOVEA CENTRALIS

CONFIDENTIAL

CHAPTER 8 - THE PROTECTION AFFORDED BY CLOTHING

8.1. Introduction

Ordinary clothing, especially that worn in temperate and cold climates where the outer garments are usually made of wool, provides valuable protection against flash burns over the area it covers. The face and hands and, in the case of women and children, the legs, are unlikely to be adequately covered, but this can be corrected by the wearing of gloves and long trousers. Satisfactory protection of the face is more difficult to achieve without seriously impeding vision. Useful protection can be secured by arranging for the head and neck to be well covered and for the face to be heavily shaded by a projecting peak and partially obscured by hanging fabric. Japanese experience showed that burns through clothing were more likely to occur where the garment was drawn tightly in contact with the skin. The great value of light coloured clothing was also demonstrated, but light colours conflict with the camouflage requirements of the Services.

A great many factors enter into the protective qualities of a clothing assembly against thermal radiation, amongst which may be mentioned:-

(i) the number of layers;

(ii) the reflectance of the outer and subsequent layers;

(iii) the transmittance of the layers;

(iv) the space between the layers and between the innermost layer and the skin;

(v) the thermal capacity of each layer;

(vi) the 'flashing' temperature of the outer layer.

Other factors are undoubtedly involved, and the behaviour of multi-layer assemblies is particularly complicated. Moreover, the properties of the fabric change during exposure to the radiation. It has not proved possible to relate burn protection to fabric properties in any simple way. In the following Sections of this Chapter some account is given of laboratory investigations of thermal effects on clothing, and also of full-scale trials results.

8.2. Laboratory Studies with Animals

The protection afforded by clothing against high intensity radiation pulses has been the subject of laboratory studies over a number of years at the University of Rochester, New York, under contract with the U.S. Atomic Energy Commission. The source of radiation used in this work is a carbon arc which, in conjunction with a 24 inch ellipsoidal mirror, provides intensities up to approximately 34 cals/cm^2/sec. The shutter, as normally operated, gives a trapezoidal pulse, but a pulse shape resembling that from an atomic explosion can also be reproduced.

The workers at Rochester do not consider that any instrumentation methods so far developed can be reliably used to predict the probability of a second degree burn. They accordingly employ small white pigs of about 20 lbs. weight, the skin of these pigs being structurally similar to that of man and responding similarly to thermal stimuli. Thus, for 0.3 sec. exposures, the average level of thermal energy required to produce a second degree burn on the human skin was 4.0 cals/cm^2. See also Chapter 7, Section 7.3.2. - Flashburns. It has also been shown that the burns produced on pigs by the Rochester equipment are similar in their characteristics and healing properties to those observed when the animals are exposed to the thermal radiation from an atomic weapon.

Nevertheless, in drawing conclusions from the Rochester data, it should be kept in mind that the latter are concerned with the probability of producing second degree burns on anaesthetised animals when small areas (1.7 cm. diameter) are exposed to trapezoidal thermal pulses. The results do not necessarily apply directly to human skin, to larger burn areas, to other degrees of burn, or to different pulse shapes.

It has been shown that the protection afforded by fabrics, particularly multi-layer assemblies, varies in a complicated way with irradiance and exposure time. A specified thermal dose applied at different exposure times will produce effects which will depend on whether the outer layer bursts into flame, acts as a thermal reservoir supplying heat to the skin after completion of the exposure, is destroyed with the dissipation of energy, or is destroyed before the end of the exposure so that the radiation impinges on the next layer. Studies at fixed exposure times are therefore of limited value, and data must be obtained over a range of exposures and intensities.

The value of an air space between the fabric and the skin is very marked. For an exposure time of 0.5 seconds, the protective index (defined as the ratio of the approximate dose required for a 50% probability of producing a second degree burn under the fabric, to the corresponding value for bare skin) for a 9 oz. olive-green cotton sateen fabric, rose from 1.5 when the cloth was in contact with the skin to 3.0 when it was separated by a 2 mm air gap. When a two-layer assembly of sateen over knitted underwear fabric was separated from the skin by a 5 mm air gap, the protective index showed a 4-fold increase (References (1) and (2)).

The effect of applying flame-proofing treatment to cotton sateen fabrics was also examined at Rochester, U.S.A. Such proofings usually involve the impregnation of the cloth with some 15-20% of flame-proofing chemicals; thus, the thermal properties of the cloth are affected and the burn protection on the flame-proofed cloth in direct contact with the skin may be slightly inferior to that of the corresponding unproofed cloth. The mechanism of action of some flame-proofing treatments is to modify the thermal degradation of cellulose so as to favour the production of tars rather than inflammable gases. When a flame-proofed cotton fabric is

/exposed

exposed to high intensity radiation, these hot tars may, in some circumstances, distil onto the skin and cause serious burns. Flame-proofing treatments are however, valuable for application to the outer layer of two-layer cotton assemblies such as might constitute a tropical kit. If the outer layer is not flame-proofed it ignites with sustained burning, which itself causes burns. It should be noted that this flaming does not occur when the fabrics are in skin contact. This effect is shown in the following results:-

Material	Protective Index	
	Contact	Separated 5 mm from skin
5 oz. Green Cotton Oxford Cloth over knitted undergarment fabric	5.5	8.5
5 oz. Green Cotton Oxford Cloth with outer flame-proofed fabric	4.0	11.1

The protective values of clothing assemblies given by Rochester are substantially lower than those reported by the U.S. Naval Materials Laboratory, where the critical energy required to produce a burn was assessed by a heat-sensitive backing paper. On the basis of Rochester's figures, which may be conservative, the following estimates are given for the probable performance of military clothing:-

No. of Layers	Type of Uniform	Energy required to produce a casualty cals/cm^2
2	Tropical, light weight	7
4	Temperate	40
6	Cold weather, heavy wool	100

The temperate and cold weather uniforms therefore give a high measure of protection, which could be further increased by wearing additional layers. The main problem is to improve face and hand protection to a similar degree. Tropical clothing presents considerable difficulty, but re-design to give a looser fit, and the application of a permanent flame-proofing to the outer layer, might lead to some improvement.

Further information on the thermal effects on textiles and clothing is given in Section 4.2.1. of Chapter 4.

References

(1) U.S. University of Rochester, Report No. U.R.354 (P.50377) "Protective Qualities of Fabric Expressed by a Protective Index".

(2) U.S. University of Rochester Report No. U.R.355 (P.50376) "Influence of Exposure Time and Irradiance on the Thermal Protective Qualities of Two-Fabric Assemblies".

8.3. Full-scale Tests of Thermal Damage to Military Uniforms

The effect of thermal radiation from a weapon of about 15 KT yield, upon full-scale Service clothing assemblies exposed on tailors' dummies, was studied at Operation Buffalo (Reference (1)). The object of the tests was to compare the effects on clothed men with the effects predicted from observations made on small fabric specimens. The results obtained are summarised in Table I.

TABLE I - Effect of Thermal Radiation (Approx. 15 KT Weapon) on Surface Layer of Uniforms and Fabric Sample Assemblies

Thermal Dose Cals/cm^2	Battledress		Combat Suit		Tropical Suit KD/	
	Full Scale	Sample	Full Scale	Sample	Full Scale	Sample
1.3	-	0	-	0	-	0
2.0	-	0	-	0	-	0
2.6	-	0	-	0	-	0
3.8	-	0	-	0	-	0
5.0	-	2	-	0	-	0
7.2	-	3	-	3	-	2
9.0	2	3	2	4	5*	4
12.5	2	3	3	4	5*	-
16.5	2	4	4	5	5*	-
24.5	4	4	5	5	5*	-
33.0	4	-	5	-	5*	-
51.0	5	-	5	-	5*	-
65.0	-	-	-	-	-	5
85.0	-	-	-	-	-	-
115.0	-	-	-	-	-	5

Code:- 0 = no apparent damage

1 = just perceptible scorching

2 = slight scorching

3 = moderate charring

5 = complete destruction

* = complete destruction of whole assembly and dummy

/ = the tropical suit KD consisted of drill trouser and cellular jacket, whereas the only fabric sample used for comparison was drill.

Conclusions

The following conclusions are made in Reference (1).

(i) The current serge battledress and sateen combat suit, give excellent protection against thermal radiation, except that both types naturally fail to cover all bare skin.

(ii) The R.A.F. Service dress also gives excellent protection, but it is considered that the dark blue colour may slightly reduce its protection compared with khaki battledress.

(iii) The tropical uniform offers very little protection and may in fact increase the effect of thermal radiation by ignition.

(iv) The R.A.A.F. flying suit is similar to tropical uniform in that it easily ignites and is therefore unsatisfactory with respect to thermal protection.

(v) The oversuit tank crew is unsatisfactory because of the low melting point of the plastic outer layer.

(vi) It is considered that the use of small fabric samples to test the effects of thermal radiation on uniforms is reasonably satisfactory.

Reference should also be made to Section 4.2.1 of Chapter 4, which gives an account of thermal effects on textiles, including Service uniform fabrics.

References

(1) A.W.R.E. Report T11/58. Operation Buffalo Target Response Tests, Materials Group, Part 6. "The Effect of Thermal Radiation from a Nuclear Explosion on Service Uniforms. (Confidential)

8.4. Critical Radiant Exposures for Burns under Clothing

The complexity of the interrelations among the factors which control the protective value of clothing assemblies (see Section 8.1) makes an accurate prediction extremely difficult. Table 1 lists estimates of radiant exposures required to effect burns under clothing and is based on information obtained from References (1) and (2). These values are considered representative of average field conditions, but it should be remembered that they are dependent upon many variables which are not easily defined, and are probably correct within a factor of 2. Additionally, in extremely cold or wet weather, the thermal intensities required for burns are considerably increased.

Table 1

Critical Radiant Exposures for Burns under Clothing
(expressed in cal/cm^2 on outer surface of cloth).

Clothing	Burn	1 KT	100 KT	10 MT
Summer Uniform	1°	8	11	14
(2 layers)	2°	20	25	35
	3°	25	33	44
Winter Uniform	1°	60	80	100
(4 layers)	2°	70	90	120

References

(1) Capabilities of Atomic Weapons (1957) U.S. Dept. of the Army TM 23-200. p. 6-4 (Confidential)

(2) Staff Officers' Field Manual - Atomic Weapons Employment. U.S. Dept. of the Army, FM 101-31 (1956) p.72. (Secret Atomic)

PART VII - DAMAGE BY NUCLEAR RADIATION

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CHAPTER I - INTRODUCTION

At the instant of detonation of any atomic or thermonuclear weapon gamma rays and neutrons are emitted at high intensity for a brief period of the order of a microsecond. This radiation is followed by emission of alpha particles, beta particles, gamma radiation and neutrons from the fission products and bomb residues in the cloud. As the cloud rises and cools and is later dispersed by the wind these fission products and residues condense and, with any surface material which may have been sucked up into the cloud, ultimately return to the surface as fallout. The radiation from fallout consists mainly of alpha, beta and gamma activity. The two cases are distinguished by the terms 'initial' and 'residual' nuclear radiation, but as the fission products are extremely active immediately after formation, some authorities prefer to consider nuclear radiation from the cloud as part of the initial radiation for a period which then requires definition. One minute is commonly taken as the demarcation point, being a time in which a high proportion of the initial radiation will have been emitted. Half the initial gamma radiation appears within 0.5 of a second in the case of a 20-KT bomb, and within 5 seconds in the case of a 5-MT bomb.

It appears unlikely that nuclear radiations will be of sufficient intensity outside the radius of total annihilation to affect appreciably the chemical or mechanical properties of materials, except in certain special cases such as photographic and perhaps electronic equipment which are covered in Part VIII. The principal importance of these radiations is therefore on account of their biological effects, especially on man.

The most important initial nuclear radiations are high energy gamma rays (1-10 Mev) and neutrons. The hazard from fallout depends to some extent on whether it is external i.e. from material lying on the ground, or internal, from material taken into the body via the lungs, mouth or open wounds. In the external case gamma activity is the principal hazard. The beta activity is of relatively short range in materials so that its effects are limited to surface tissues, and the alpha particles are absorbed even in a few inches of air. The case is very different for internal deposition, as certain chemical are strongly held in the body in places where their short range but heavily ionising radiations can do considerable damage.

The accounts of each type of radiation from a weapon of a given size under various conditions of burst are given in Reference (1), Chapters 5 and 6. This reference also discusses the energy spectra of the radiations and their angles of arrival at a target at a given distance. For ease of reference certain of this information is summarised in this part of the manual, but Reference (1) should be consulted for fuller details. An unclassified account is given in Reference (2). The importance of neutron gammas is discussed in Reference (3).

In particular it must be emphasized that there is no precise general relationship between the blast and thermal yields of weapons and their output of initial nuclear radiations. It depends on the design of the particular weapon. Data for neutron output are particularly sensitive in this respect and the figures normally quoted for neutrons should be regarded as lower estimates which may be exceeded by factors of 10-30 in special cases.

Chapters 2 and 3 of Part VII discuss quantitatively the various biological effects on man and give the maximum dose permissible in various circumstances. Chapters 5 and 6 cover the extent to which radiation from a given source may be reduced by shields of various materials. Chapter 7 discusses the nature and movements of fallout material, the removal of which is considered in Chapter 8. Part VII concludes with a brief review of standard Radiac instruments for the routine monitoring of various types of activity.

References

(1) A.W.R.E. Manual on The Effects of Atomic Weapons, 1955. (Secret/Atomic/U.K.Eyes Only)
(2) The Effects of Nuclear Weapons. U.S.Atomic Energy Commission, 1957.
(3) On the Origin of the Initial Gamma Radiation. Stewart K. 1957 Tripartite Conference Paper AWEC/P(57)213. (Secret/Atomic)

CHAPTER 2 - BIOLOGICAL EFFECTS OF NUCLEAR RADIATION

2.1. The Nature of Biological Effects on Man

As explained in the introduction to Part VII, the nuclear radiation effects of an atomic explosion may be divided into two categories, namely, the initial radiation (gamma rays and neutrons) and the residual radiations (gamma rays, alpha and beta particles). Although different radiations may cause ionisation by different mechanisms and to varying degrees, the ultimate biological response of cells composing living tissue exposed to these radiations is to suffer cellular damage or destruction.

The effects of nuclear radiations on man depend however, not only on the total radiation absorbed, but on the rate of absorption. The generally accepted explanation for this is that if the dose-rate is small the damaged tissues have a chance to recover, at least partially, but where intensive radiations are received the recovery cannot keep pace with the damage. This fact makes it necessary to distinguish between acute exposure (a single short dose of radiation) and chronic exposure (a prolonged dose). Exposure to the initial radiations from an atomic bomb, which are taken as being of one minute's duration, may therefore be regarded as acute.

The gamma (or X-) radiation dose received by an individual is described in terms of the roentgen unit (r) (see Glossary for definition). It is a measure of the strength of the radiation field at a given location, and the radiation dose in roentgens is therefore referred to as an "exposure dose". Neutron radiation dose may be estimated by the rem (roentgen-equivalent-man) unit, which is the amount of energy absorbed per gram of mammalian tissue to give the same biological effect as one roentgen of gamma or X- radiation.

Table 1, taken from Reference (1), gives an approximate indication of the early effects on human being of various acute doses of radiation, assuming exposure of the whole body. Individuals may, however, vary considerably in their reactions to nuclear radiations.

TABLE 1

Acute Effects of Whole Body Penetrating Ionizing Radiation on Human Beings

Dose in 1 week	Effect
0-150 r	No acute effects - serious long term hazard.
150-250 r	Nausea and vomiting within 24 hours, minimal incapacitation after 2 days.
250-350 r	Nausea and vomiting in under 4 hours. Some mortality will occur in 2-4 weeks. Sympton free period 48 hours-2 weeks.
350-600 r	Nausea and vomiting under 2 hours. Mortality in 2-4 weeks, or prolonged incapacitation.
600 r	Nausea and vomiting almost immediately. Mortality in 1 week.

Table 2, also from Reference (1), summarises the estimated effects of doses received over periods up to three months.

The residual radiations arising from fission products may constitute a chronic hazard, either as external or internal radiation. The former applies to instances in which the source of radiation lies outside the body and the latter refers to cases where the source is taken into the body by ingestion, inhalation, or through breaks in the skin. The effects of residual radiation from external sources are dealt with in Section 2.3, and in some respects the results of chronic doses of such radiation may be expected to be similar to those for acute doses, the severity depending on dose-rate and total accumulated dose.

The hazard caused by a radioactive substance taken into the body will depend on the solubility and chemical and physical properties of the substance, which determine how it is absorbed. The effects of such absorption may be long-delayed, but ultimately very serious; these effects are described under Section 2.4.

The ultimate injury from radiation received from mixed and intermittent sources will be a combination of the separate radiation effects to which an individual is exposed. Thus the dose from initial gamma radiation must be added to the 'rem' from neutrons and the gamma dose from residual radiations. The dose from external beta radiation is assessed separately, since it causes a surface effect rather than internal injury.

Other types of injury, when combined with sub-lethal exposure to nuclear radiation (e.g. about 150-250r) are expected to produce more severe results than in the absence of nuclear damage. Thus sub-lethal thermal burns combined with exposure to nuclear radiation are expected to produce earlier and more severe reaction than would occur in uncomplicated burns of similar degree. Reference (2) describes observations which were made of thermal burns on pigs and dogs which had also received fatal or near-fatal doses of nuclear radiation. The uninterrupted healing of severe burns in pigs dying of radiation sickness was a stricking phenomenon. If the burn progressed to the point of partial epithelialization, then healing proceeded in spite of mortal radiation sickness. But granulating biopsy wounds or burns became gangrenous and sloughed when radiation sickness appeared. This may indicate that all efforts should be made to promote healing of burns and that all definitive surgery should be done early in those who have received significant amounts of ionising radiation.

A recent review of the biological effects of ionising radiations is given in Reference (3). Reference (4) summarises much useful material, including observed biological effects of radiation, medical evaluation of personnel, treatment of injuries, and permissible doses. Extensive bibliographies are given.

It should be noted that only the immediate biological effects of nuclear radiations are dealt with in this chapter. A discussion of the genetic effects is outside the scope of this Manual, but a review of this subject will be found in Reference (3).

References

(1) Alpen, E. L. "Radiological Hazard Evaluation". 12th Tripartite Conference on Toxicological Warfare (1957) (Secret/Discreet)

(2) Report UR.254 - "Thermal Burns from the Atomic Bomb". University of Rochester, (N.Y.), Atomic Energy Project.

(3) The Hazards to Man of Nuclear and Allied Radiations - Medical Research Council (HMSO Cmd. 9780).

(4) U.S.A.F. Radiobiology Guide. Wright Air Development Center, Technical Report 57-118 (April, 1957).

TABLE 2

Estimated Medical Effects of Radiation Doses Expressed as Percentage of Working Force Affected*

Total Dose (r)	Duration of Continuous Exposure					
	1 day	3 days	1 week	1 month	3 months	Effects
0 to 75	0% sick				0% sick	None
100	2% sick	0% sick			0% sick	None
125	15% sick	2% sick	0% sick		0% sick	None
150	25% sick	10% sick	2% sick	0% sick	0% sick	None
200	50% sick	25% sick	15% sick	2% sick	0% sick	Some late effects
300	100% sick 20% dia	60% sick 5% die	40% sick	15% sick	0% sick	Some late effects
450	100% sick 50% die	100% sick 25% die	90% sick 15% die	50% sick	0- 5% sick	Some late effects
650	100% sick 95% die	100% sick 90% die	100% sick 40% die	80% sick 10% die	5-10% sick	Some late effects

*This table applies to healthy, young adults under usual working conditions.
The percentage of fatalities will be decreased with adequate medical treatment.
The percentage figures are based on an interpretation of the best current available evidence and may be changed as more information is accumulated.

2.2 Effects on Man of Initial Radiations

We are concerned in this section with gamma rays and neutrons produced during the first minute following a nuclear explosion. This time is short compared with the biological response times, so that the biological effect for a given total dose of initial radiation is approximately independent of dose-rate. In the case of a surface burst the dose received from secondary sources during the first 24 hours may be counted as a part of the initial dose.

The clinical results of exposure to ionising radiations may be considered under four headings:-

(a) The effects of an overwhelming dose of radiation (over 5,000 roentgens).

(b) Supra-lethal radiation injuries (over 600 roentgens)

(c) Lethal radiation injuries (300-600 roentgens)

(d) Sub-lethal radiation injuries (100-300 roentgens).

(a) Massive doses of radiation will seldom be encountered in the absence of severe heat and blast effects, but occasionally the two other effects may have been prevented by shielding. In such cases death will be comparatively early (within a few hours or days) and incapacity will be almost immediate.

(b) Most of the cases suffering supra-lethal irradiation will vomit within the first two or three hours, and continue with generalised malaise during the first day or two, with a return of gastro-intestinal symptoms by about the fourth day after exposure. Persistence of these symptoms is of bad prognostic significance and it is likely to be followed by soreness of the mouth and pharynx, with rising temperature towards the end of one week and death at latest by the tenth day after exposure. Epilation (loss of hair) is not likely to have developed in these cases, and haemorrhages will not be marked. There will be some intestinal ulceration.

(c) Lethal radiation injury will be caused by exposure in the region of 300-600 roentgens and will result in approximately 50 per cent deaths. Nausea and vomiting will occur during the first 24 hours. This will be followed by a latent period, with no definite symptoms, lasting for about a week. During this time if a blood count can be performed a fall in lymphocyte count will be detectable. The first signs of epilation may be detectable after nine or ten days, and the fall of hair will be marked after fourteen days. This effect may be absent if the hair of the scalp has been partially protected by the wearing of a steel helmet.

The main lesions of this group will be associated with haemorrhage, necrosis (cell destruction), and secondary infection. Recurrence of loss of appetite and malaise begin about the middle of the third week after exposure, and towards the end of this week there may be a rise in temperature. By this time the white cell count is usually at a low level. Approximately three weeks after exposure there is soreness of the mouth, together with anaemia, due to impairment of red cell formation and haemorrhage, which increases and becomes more marked when petechial (skin) and internal haemorrhages occur.

Infection, in the absence of anti-biotics, rapidly becomes generalised. In such cases there is little or no cellular reaction. Ulceration of the

bowel frequently occurs. Death associated with haemorrhages most commonly occurs towards the middle of the fourth week after exposure. Mortality is about 50 per cent.

Those who survive this severe illness are left in a weakened emaciated state with poor ability to overcome infection. In some of them, co-existing diseases such as tuberculosis light up and recovery takes a long time; in most cases however, recovery is never complete. Testicular damage causes temporary sterility, although in most cases recovery will eventually occur. A dose of the order of 300r to the overies will cause permanent sterilisation.

Late effects among the survivors of severe radiation injury include an increased tendency to the development of leukaemia and minor cataracts, and there is also the probability of genetic effects which will only be apparent in subsequent generations.

In the early stages of pregnancy, abortion, possibly followed by the death of the mother, may occur.

(d) In cases where a sub-lethal degree of exposure of radiation has occurred there will be some nausea and vomiting several hours after exposure. Following this there will be a latent period without any symptoms attributable to irradiation. This will be much longer than for cases of lethal exposure. In general, the greater the length of the period without symptoms the better will be the prognosis. Towards the end of the third week there may be some tendency to epilation, followed by loss of appetite and general malaise. Soreness of the mouth, anaemia, gastro-intestinal symptoms, and even haemorrhages may appear to a much less extent than among severe cases, and by the end of the fourth week most of the patients will begin to recover, although pale, anaemic and somewhat emaciated. In general, unless there are complications, recovery will be the rule.

Minor manifestations of radiation damage will also occur. In many such cases there will be no symptoms, but careful examination, particularly of the blood system, would show evidence of radiation damage. In general, such cases should not, if possible, be further exposed to radiation.

The injury effects which have just been described are summarised in Table 1, and Figure 1 (taken from Reference (1)) gives the percentage of casualties from nausea and vomiting within two hours, as a function of gamma radiation dose received. Figure 2 (from Reference (2)) gives the incidence of sickness and death due to acute exposure to various doses of nuclear radiation.

Neutron Effects

The neutrons emitted in a nuclear explosion can, like gamma rays, penetrate considerable distances in air and cause similar biological damage. More than 99 per cent of the neutrons produced by the fission of uranium or plutonium are released within a micro-second of the explosion, and these are described as prompt neutrons. The remainder of the neutrons, referred to as delayed neutrons, are produced subsequently by the decay of certain types of fission fragments. Delayed neutrons are not significant for biological consideration. Following an explosion, neutrons are also produced by the action of gamma rays on bomb materials, but the number is relatively very small and may be ignored.

Neutrons, like gamma rays, can cause radiation sickness and death, although the timing of the illness may be rather different. The neutron radiation dose may be estimated in rem (see Section 2.1) or in rads, where

1 rad is the unit of absorbed dose, equal to 100 ergs per gram of tissue. The relative contribution of neutron and gamma radiation to total biological dose is shown in Figure 3, taken from Reference (2).

Neutrons transfer energy to the tissue by a different mechanism from that of gamma rays, and produce greater biological damage. The relative biological effectiveness (RBE) is the ratio between the quantity of energy delivered to the tissue by gamma rays compared with neutrons to produce the same biological effect. For many observed biological effects neutrons appear to have an RBE 1-4 times that of gamma rays, but in some instances values as high as 15-30 have been found (Reference(1), page 184). The production of cataracts (lens damage) appears to have an RBE of 4-8, and this may be a limiting factor in determining permissible exposure to neutrons. In Reference (2), page 468, it is recommended that a value of 1.7 be taken for the RBE for casualties from bomb neutrons. This figure has been obtained from observations on mice, but some confirmation is given by analysis of data on radiation injury and death after the nuclear explosions in Japan.

Further more detailed accounts of the biological effects of initial radiations may be obtained from Reference (2), page 466, and References (3), (4), and (5).

References

(1) Capabilities of Atomic Weapons, U.S. Armed Forces Special Weapons Project TM 23-200 (1955) (Confidential/Atomic)

(2) The Effects of Nuclear Weapons, U.S.A.E.C. (1957).

(3) Bugher, J. C. "Delayed Radiation Effects at Hiroshima and Nagasaki". Nucleonics, Vol. 10, No. 9, p.18 (1952).

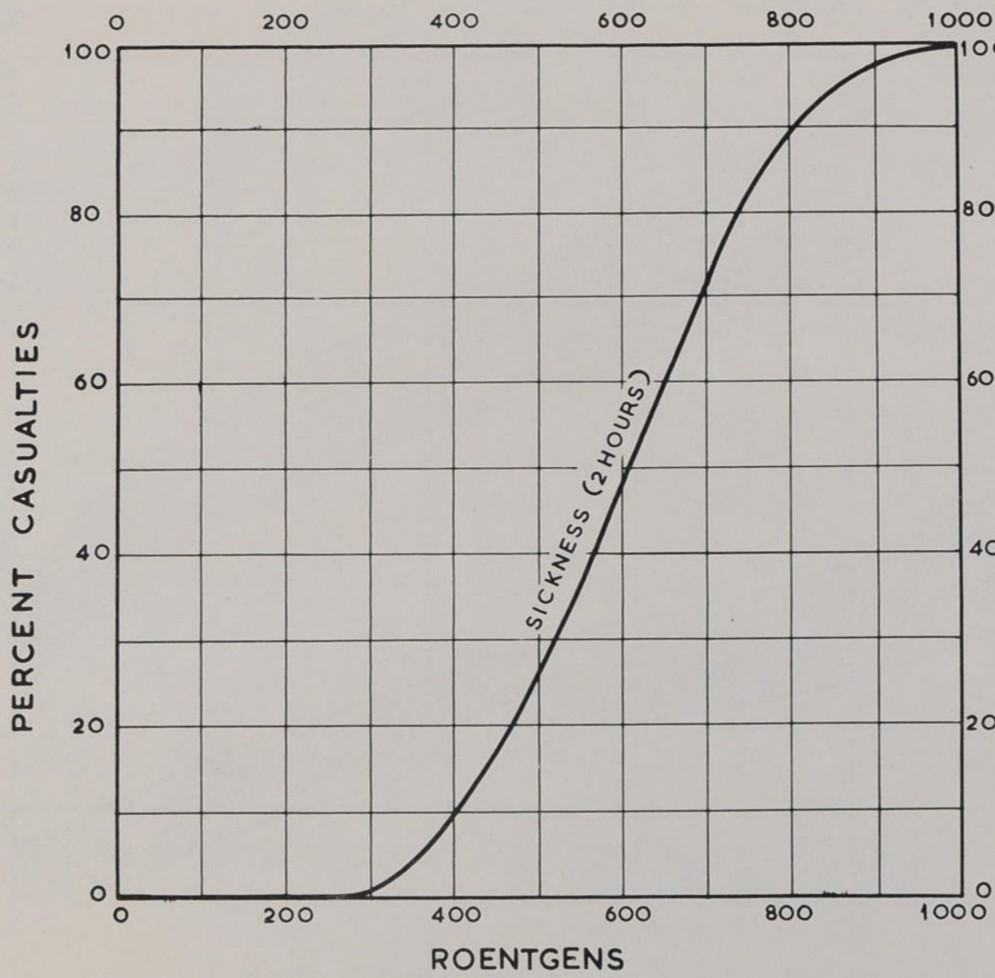
(4) Hempelmann, L. H., Lisco, H., and Hoffmann, J. G. "The Acute Radiation Syndrome: A Study of Nine Cases and a Review of the Problem". Ann.Int.Med., Vol. 36, p.279 (1952).

(5) Oughterson, A. W., and Warren, S. (Editors) "Medical Effects of the Atomic Bomb in Japan", National Nuclear Energy Series Division VIII, Vol. 8, McGraw Hill Book Co., New York, 1956.

TABLE 1

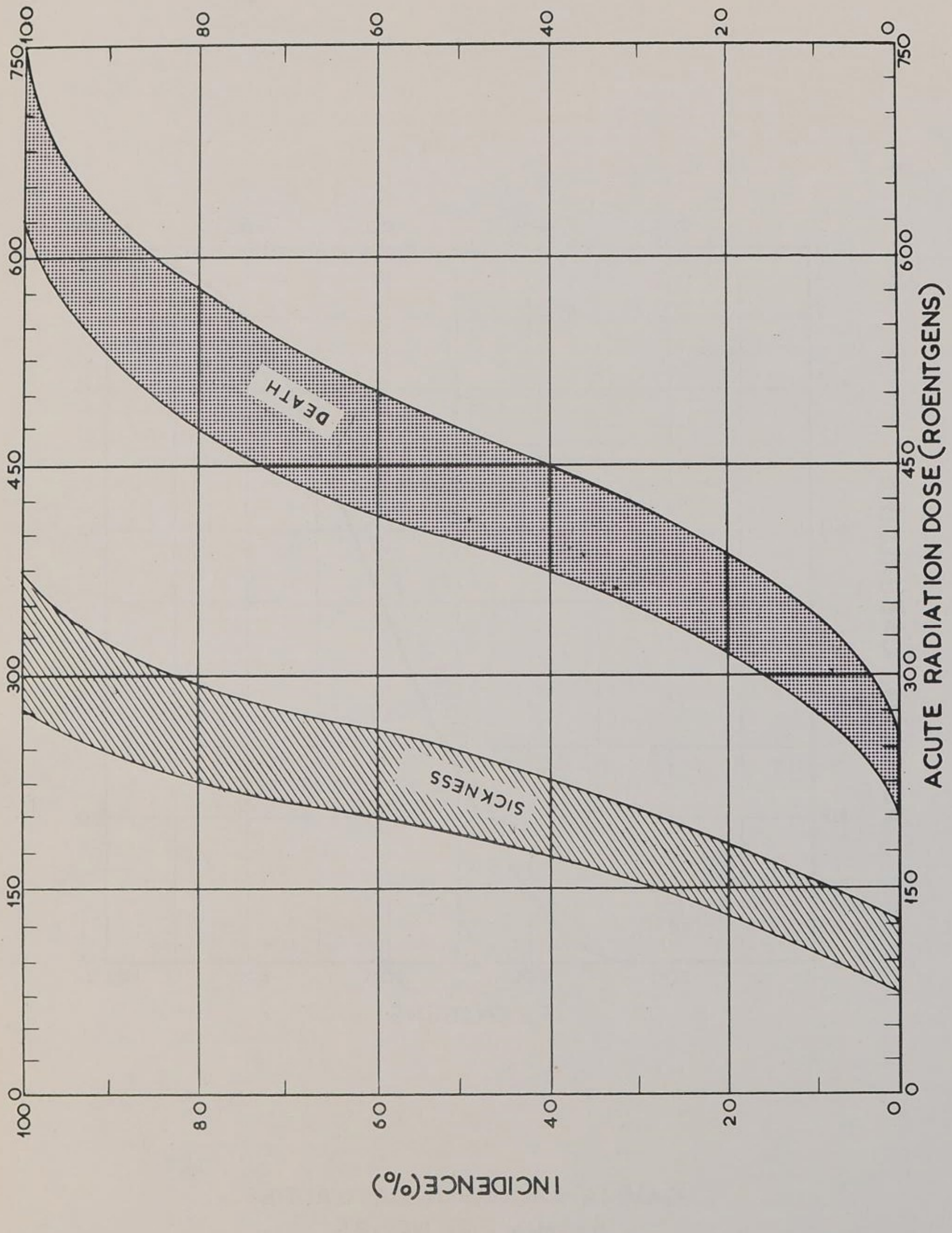
The Clinical Symptoms of the Radiation Syndrome

Average days after exposure	Supra-Lethal Radiation Injury (over 600 r)	Lethal Radiation Injury (300-600r) 50% Deaths at 450r	Sub-Lethal Radiation Injury (100-300r)
0	Nausea and vomiting within 1-3 hours	Nausea and vomiting after 2-4 hours	Variable, depending on the individual
1	Generalised malaise	No definite symptoms	-do-
2-3	Malaise and anorexia	-do-	-do-
4	Nausea and vomiting	-do-	-do-
5	Vomiting and diarrhoea	-do-	-do-
6	Soreness of mouth and throat	-do-	-do-
7	Fever	-do-	-do-
8	Rapid emaciation	-do-	-do-
9	Death	Beginning epilation	-do-
10	Mortality probably 100%		-do-
17		Anorexia and malaise	-dop
18			Beginning of epilation
19		Fever	Anorexia and malaise
20		Gangrene or soreness of mouth	
21			Sore mouth
22			Pallor
23		Pallor	
24			Diarrhoea
25		Petachiae	Moderate emaciation
26		Mucosal haemorrhage	
27		Diarrhoea	Recovery unless complicated by previous poor health or superimposed injuries or infections
30		Rapid emaciation Death (Mortality probably 50%)	

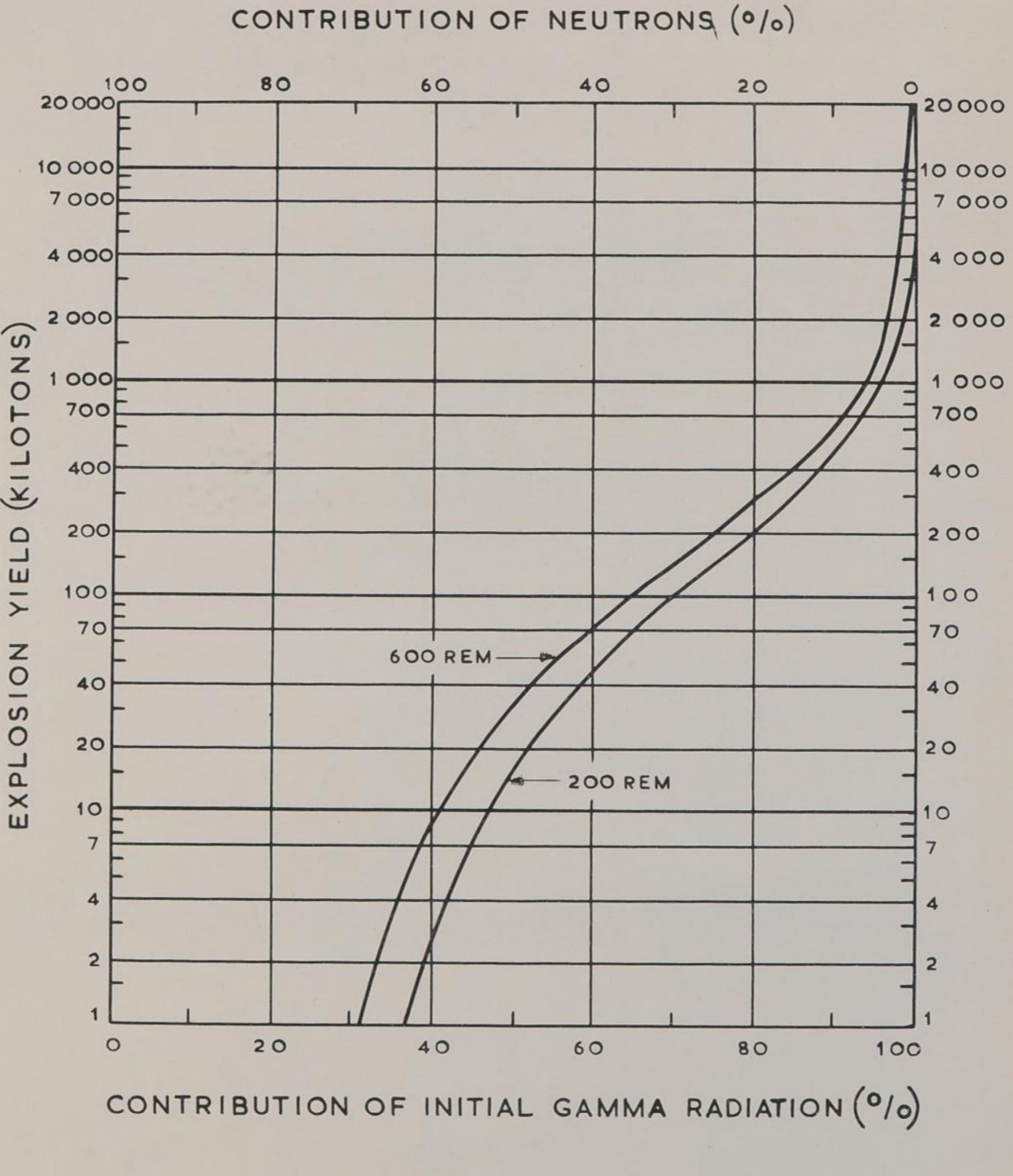


GAMMA RADIATION CASUALTIES
WITHIN 2 HOURS

UNCLASSIFIED



INCIDENCE OF SICKNESS & DEATH DUE TO ACUTE EXPOSURE TO VARIOUS DOSES OF NUCLEAR RADIATION



RELATIVE CONTRIBUTION OF NEUTRON AND INITIAL GAMMA RADIATION TO TOTAL BIOLOGICAL DOSE

2.3. Effects on Man of External Residual Radiations

If radiation from surface contamination and fallout is to have any biological effect it must pass through the horny layers of the skin. Because of their very short range in air, and even shorter range (about 0.05 mm) in tissue, alpha particles are of no importance as an external radiation hazard.

Beta particles: These may penetrate a few millimetres in tissue, but do not reach the bone marrow or other inner parts of the body. Skin injuries ranging from reddening to blisters and sores may result from exposure to beta emitters, and these injuries can cause incapacity similar to that resulting from thermal burns. Depending on the dose received, the incapacity can begin as early as 4-6 hours, or as late as ten days, and the resulting injury may last for several months. The probability of exposed persons obtaining beta burns from fallout may be considerably reduced by immediate action such as bathing and change of clothing. The longer fallout remains in contact with the skin the more severe and extensive the beta burn is likely to be. Radiation sickness is not expected to accompany the skin injuries caused by beta particles. The acute effects of ionising radiation on the skin are given in Table 1, taken from Reference (1). The doses in this Table are expressed in 'rads', where 1 rad is by definition the unit of absorbed dose, and equals 100 ergs per gram of tissue.

TABLE 1

Acute Effects of Ionising Radiation on Skin

Estimated dose required in 1 week (rad)	Effect
0-600	No accute effects
600-2,000	Moderate early erythema
2,000-4,000	Early erythema under 24 hours. Skin breakdown in 2 weeks.
4,000-10,000	Severe erythema in 24 hours. Severe skin breakdown in 1-2 weeks.
10,000-30,000	Severe erythema in 4 hours. Severe skin breakdown in 1-2 weeks.
30,000-100,000	Immediate skin blistering (less than 1 day).

Gamma rays, being much more penetrating than alpha or beta particles, are the most hazardous type of external residual radiation. The mean energy of the gamma ray photons from residual radiations is about 0.7 Mev compared with about 3 Mev for initial gamma radiations. Residual gamma radiation is therefore less penetrating than initial radiation.

Little evidence is available of the ultimate effects of prolonged human exposure to moderate gamma radiation, such as might be experienced in a contaminated area, but the effects of tissue recovery may influence the degree of injury sustained. The total dose received is the basic criterion for injury to personnel; but if the time of exposure increases, then the total dose required to produce incapacity increases also. For example, on the average, 50 percent deaths would occur in persons exposed to an acute dose of 450r. On the other hand, exposure to 15r per day for 30 days would produce limited casualties and probably no deaths, (see Table 2, Chapter 2, Section 2.1). On a lesser scale of exposure it is expected that persons who received 0.1r daily for years would show no ill effects. In general, the clinical symptoms and biological effects of chronic doses of gamma radiation over the whole body are expected to be similar to those for acute doses, the severity of the effects increasing with dose rate and cumulative dose.

Reports on the effects on humans of accidental exposure to radioactive fallout from an atomic test are given in References (2), (3), (4) and (5). The incident in question was in March, 1954, when inhabitants of the Marshall Islands were exposed to fallout. Within about five hours of the burst, a radioactive white powder (consisting largely of lime produced by the thermal decomposition of coral) began to fall on the islands. The Marshallese spend much time out of doors and wear very little clothing, with the result that appreciable quantities of fission products fell upon and remained in contact with the hair and skin.

During the first 24 to 48 hours, a number of individuals experienced itching and burning of the skin. Within a day or two, all skin symptoms disappeared, but after a lapse of about two to three weeks, epilation and skin lesions were apparent on areas of the body which had been contaminated by fall-out particles. The lesions which developed on the exposed parts of the body not protected by clothing were mostly superficial, without blistering. Some individuals who were more highly contaminated developed deeper lesions, usually on the face or neck, accompanied by burning or itching and pain. These lesions were wet and ulcerated, becoming covered by hard dry scab. The majority healed readily, although in some cases about a year elapsed before the normal skin coloration was restored. Re-growth of hair of the usual colour and texture began in about nine weeks after exposure, and was complete in six months.

References

(1) Alpen, E. L., "Radiological Hazard Evaluation". 12th Tripartite Conference on Toxicological Warfare, (1957). (Secret/Discreet)

(2) Science, Vol. 122, No. 3181, p.1178, (1955) - "Radioactive Fallout in the Marshall Isles".

(3) Effects of Nuclear Weapons, U.S.A.E.C. (1957), pp 483-8.

(4) Cronkite, E. P., et al, "Response of Human Begings Accidentally Exposed to Significant Fallout Radiation". J.Am.Med.Assoc. Vol. 159, p.430, (1955).

(5) Cronkite, E. P., Bond, V. P., and Dunham, C. L., (Editors) - "Some Effects of Ionising Radiation on Human Beings Accidentally Exposed to Radiation and Fallout". U.S. Atomic Energy Commission - TID 5358, (1956).

2.4. Effects on Man of Internal Radiations

Radioactive substances can enter the body by inhalation, ingestion, or through open wounds. Some may pass through the gut without being absorbed, others are absorbed but are rapidly lost through excretion, radioactive decay or a combination of both. The "biological half-life" is defined as the period of time during which the amount of a nuclide deposited in the body is reduced to half its initial value by natural biological processes. The "effective half-life" of a given nuclide is the time in which the quantity in the body will decrease to half as a result of both radioactive decay and biological elimination.

Those isotopes which are absorbed and remain in sufficient concentration and for sufficient time in certain organs may cause serious damage, e.g. I^{131} (a radioactive isotope of iodine with a half-life of eight days) concentrated by and held in the thyroid may cause acute and chronic damage to the gland. Sr^{90} (a radioactive isotope of strontium with a half-life of 28 years) deposited in bone may, after an interval of time, produce malignant changes. The amount of damage produced by radioactive materials inside the body will depend on the total amount of material taken up, its intensity of localization and its effective half-life.

The lymphocytes of the blood are sensitive to internal radiation, as also are the young red blood cells. The most sensitive indication of the acute effects of an ingested fission product is a reduction in the number of lymphocytes. An early systemic effect of a relatively large dose of internal radiotion would be a reduction in the number of red and white blood cells, associated with extreme weakness and anaemia. Malignant growths may later develop in those parts of the body where the radioactive material has concentrated.

<u>Gamma rays</u> penetrate tissues relatively easily and the dose from gamma emitting nuclides is fairly uniformly distributed except where there is a tendency for the nuclide concerned to localise in a particular organ, e.g. I^{131} in the thyroid. The emission of gamma rays from substances inside the body can be detected by externally placed instruments. Where mixed fission products from atomic weapons are involved beta particles will also be emitted and there may be alpha emitting substances. As with external radiations the more sensitive tissues, especially the blood-forming organs, are the most likely to be affected.

<u>Beta particles</u> have a short range but are very damaging within their effective range. Substances which emit them are therefore more dangerous when they localise in radio-sensitive organs. In particular there is a risk of severe anaemia, and where the nuclides concerned have a long biological half-life and localise in bone, malignant disease may occur. Strontium 90 and Yttrium 90, both beta emitters, are examples of bone-seeking elements.

<u>Alpha particles</u> are even more damaging than beta particles, but their range in air and tissue is shorter than that of beta particles. Like beta emitters, alpha emitting substances cannot be directly detected by external instruments, but their presence in the body may be demonstrated by detection of the radioactive material in the excreta, expired air, or in material obtained by biopsy. Certain alpha emitting substances are very liable to cause anaemia, and even when only a very small quantity is involved they may produce malignant changes in bone. Radiu, uranium and plutonium are examples of bone-seeking alpha emitters.

Experiments on rats have shown that plutonium is 20 times more effective than radium in depressing the bone marrow function. This is apparently owing to the fact that plutonium is deposited in the surface layers of the bones rather than in the substance, and consequently its effect is more severe on the bone marrow and periosteum.

It is known from human experience that if radium is present in the bones for a long period it produces general weakness, bone changes in the jaw, malignant tumours, and bone cancer (osteogenic sarcoma). Animal experiments have shown that radiostrontium has very similar effects, and may also induce leukaemia. There is no evidence from human experience of the toxicity of radiostrontium.

Recent publications dealing with the Strontium-90 problem are given in References (1), (2), (3) and (4).

References

(1) Effects of Nuclear Weapons, pp 450-454, U.S.A.E.C. (1957)

(2) Kulp, J. L., Eckelmann, W. R., and Schulert, A. R. "Strontium-90 in Man", Science, Vol. 125, p.219 (1957)

(3) Libby, W. F., "Radioactive Strontium Fallout" Proc. Nat.Acad.Sci., Vol. 42, p.365 (1956) "Current Research Findings on Radioactive Fallout" ibid Vol. 42, p.945 (1956).

(4) Comar, C. L., Scott Russell, R., and Wasserman, R. H. "Strontium-Calcium Movement from Soil to Man" Science, Vol. 126, p.485 (1957).

CHAPTER 3 - CRITICAL DOSES AND CONTAMINATION LEVELS

3.1 Initial Radiation

Initial radiations from nuclear explosions are discussed in detail in Chapter 5 of M.E.A.W. (Reference (1)), which should be consulted for general data and background information. The purpose of this Section is to provide data relating critical doses of initial radiation (gamma rays and neutrons) to weapon yields and conditions of burst. The incident flux of initial radiation will be determined by the type and yield of the weapon, the heights of the burst and of the target, and the distance from the explosion.

Gamma radiation. Air density is the controlling factor for the attenuation of gamma radiation. The relation between initial gamma radiation dose and distance for various relative air densities is given in Figures 1A and 1B, which refer to a 1 KT air burst. The attenuation of gamma radiation by the air is reduced by the rarefaction which occurs behind the blast wave. This effect (also known as the hydrodynamic effect) may be corrected for by using Figures 2A and 2B, which give the scaling of initial gamma radiation with yield, and are obtained from Reference (2). The rarefaction effect is negligible for bursts up to 50 KT but assumes major importance in the high yield range above about 200 KT. Some values, which include corrections for typical heights of burst, are given in Part I, Appendix A, paragraph 3.4 (bound with figure 2).

For a surface explosion in the KT range, the losses due to absorption of gamma radiation and neutrons in the ground will cause the dose to be rather less than is observed for an air burst in so far as an observer on the ground is concerned. But note that for an observer in aircraft above the burst the dose will be twice that given by Figures 1A and 1B. For a surface explosion in the high yield range (greater than about 200 KT), the rarefaction effect will cause the doses to be about the same, or possibly more than would be observed for an air burst.

Information relating initial gamma dose to slant range for a 1 KT sub-surface burst is given in Figure 3, which should be used in conjunction with Figures 2A and 2B. Both sub-surface and surface bursts produce extensive fallout, and in such regions the initial gamma dose may merge with that due to residual radiation.

The percentage of gamma radiation dose received as a function of time is given in Figure 4 for kiloton air bursts, in Figure 5 for kiloton surface bursts, Figure 6 for megaton surface bursts, and Figure 7 for kiloton sub-surface bursts. These figures are taken from Chapter 5 of Reference (1)

It will be noted that for kiloton range weapons about half the gamma-rays dosage is received during the first second. Therefore at distances of the order of 4,000 feet where a dose of about 400 roentgens would be received by a fully exposed person, taking shelter behind a substantial object immediately on seeing the bomb flash, might cause a vital reduction in the dose received. Opportunity for evasive action would be greater in the case of megaton weapons since the delivery is slower.

Neutrons. Although the neutron intensity will normally be sub-lethal at distances for which a median lethal dose of gamma rays would be received, the biological effect of the neutrons will be additive to that of the gamma radiation. However, at a sufficiently high altitude (greater than about 25,000 feet) the dose from neutrons may become more important than the

initial gamma radiation dose. Figure 8 represents the maximum expected neutron dose, and Figure 9 the minimum dose, depending on the weapon design, for a 1 KT air burst at various air distances. These values may be scaled directly with yield up to 100 KT, but above this figure estimates based on linear extrapolation must be used with caution. In the case of a surface burst the proportionate doses will be changed in rather the same way as gamma radiation, but again no precise data are available. The neutron dose from a sub-surface shot will be negligible.

Figure 10 shows the number of neutrons per sq.cm. expected at various slant distances for weapon yields from 10 KT to 40 MT for air burst weapons. This figure is taken from Reference (2) and is qualified by the statement that in the case of certain high neutron flux weapons there may be as many as thirty times the given number of neutrons per sq.cm.

The neutron hazard to man is estimated from two kinds of experimental measurements. Firstly, the physical data concerning the neutron flux and energy spectrum are obtained from the use of neutron detectors. Secondly, account is taken of the biological effects of exposing animals (mainly mice) to neutron fluxes ranging from harmless to lethal. The results obtained are coupled by factors for the RBE of neutrons of various energies when compared with X and gamma rays, and it is further assumed that these results may be applied to man. Work on these lines has led to the following conclusions by U.S. workers (Reference (3)).

Neutron Energy	Dose in rem/n/cm^2
0 - 0.4 ev	5.9×10^{-11}
<1 Mev	Proportional to and decreasing with energy
1 - 3 Mev	1.6×10^{-8}
3 - 15 Mev	2.0×10^{-8}

In calculating the doses for neutron energies greater than 1 Mev, an RBE of 4 was assumed. It was observed during the U.S. experiments (Reference (3)) that for all weapon tests at which biological measurements were made, over 90% of the dose was from neutrons with energy above 1 Mev. Neutrons in the energy range 3 - 15 Mev (for which sulphur was employed as detector) contributed 25-50% of the dose, and those in the intermediate (approximately 1-3 Mev) range, 50-75%. The slow neutrons, with energies less than about 1 ev, contributed no more than 2% of the total neutron dose received at distances of biological interest.

Most of the neutrons reaching the ground would do so in such a short space of time (less than 1 second), that evasive action would not be possible.

Further discussion of neutron energies and lethality is given in Chapter 5, Section 5.2, which deals with neutron shielding problems. An unclassified account of the neutron energy spectrum of nuclear explosions is given in Reference (4).

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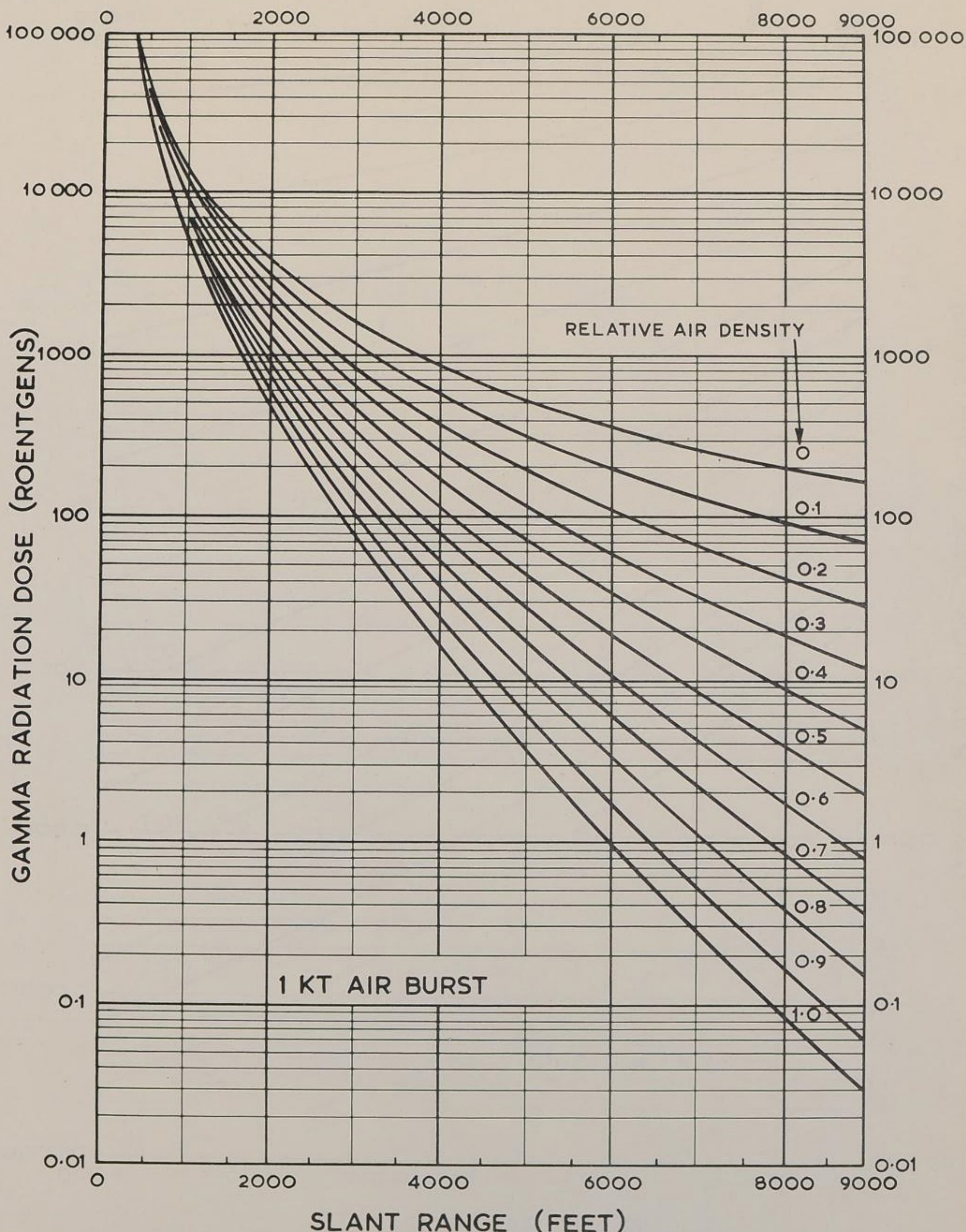
(1) A.W.R.E. Manual on Effects of Atomic Weapons, 1955. (Secret/Atomic/U.K. Eyes only)
(2) Capabilities of Atomic Weapons, A.F.S.W.P. TM23-200(1955) (Confidential/Atomic)
(3) U.S. Paper, Tripartite Conference, 1954
(4) The Effects of Nuclear Weapons, p.382, U.S.A.E.C. (1957).



INITIAL GAMMA RADIATION DOSE AS A FUNCTION OF SLANT RANGE FOR VARIOUS RELATIVE AIR DENSITIES

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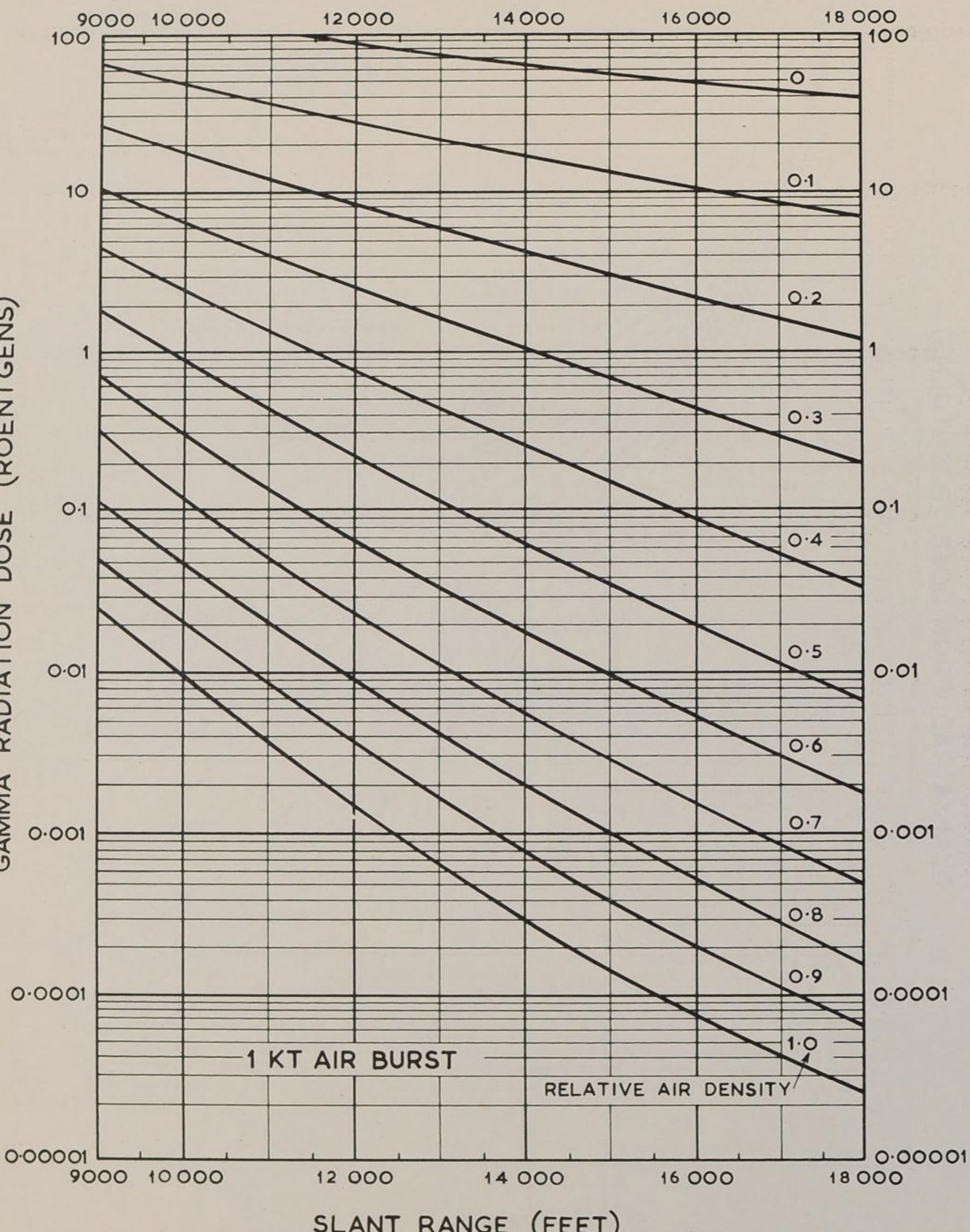

INITIAL GAMMA RADIATION DOSE AS A FUNCTION OF SLANT RANGE FOR VARIOUS RELATIVE AIR DENSITIES

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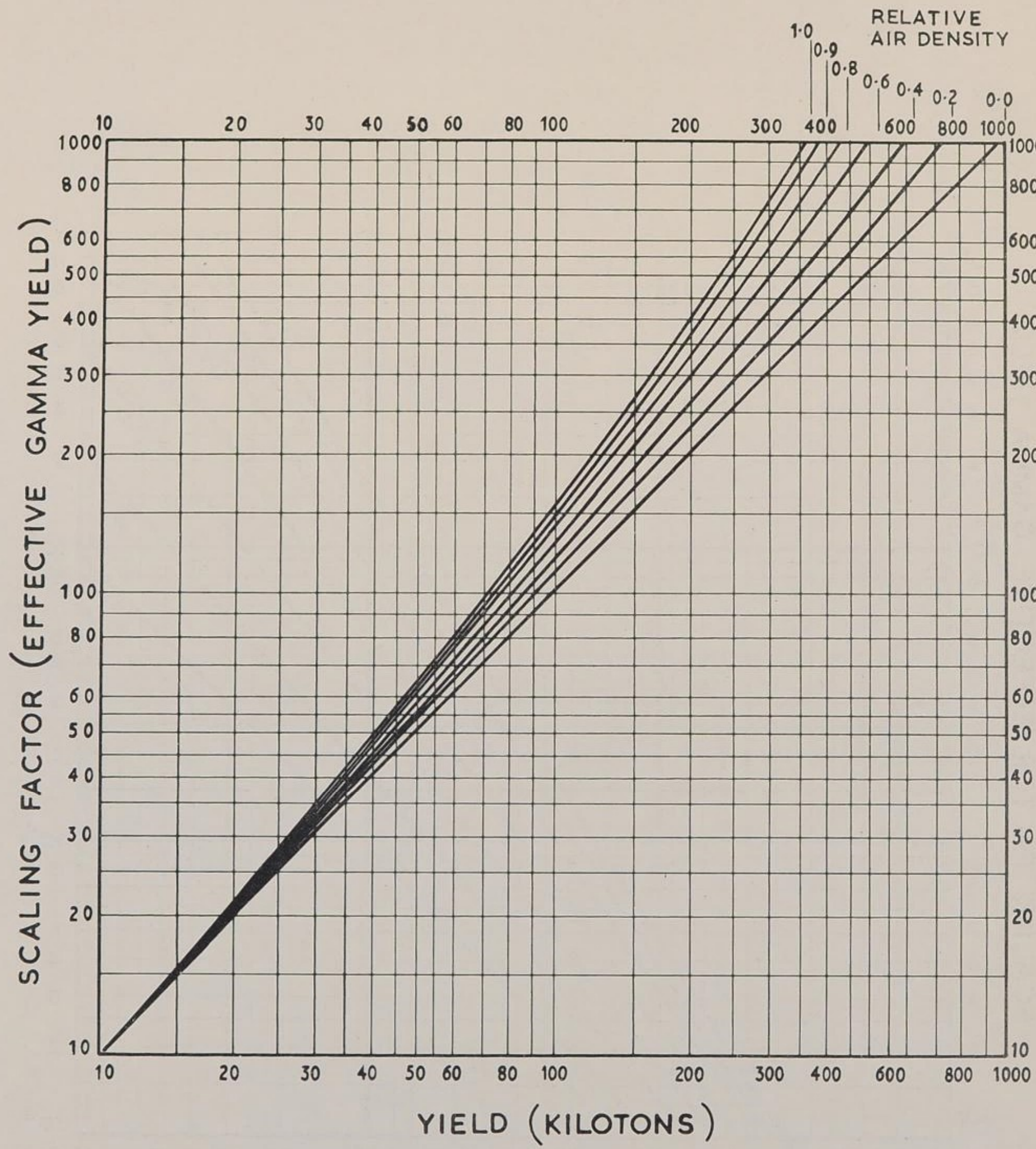

SCALING OF INITIAL GAMMA RADIATION WITH YIELD

PART VII
CHAPTER 3
SECTION 3.1
FIGURE 2 B

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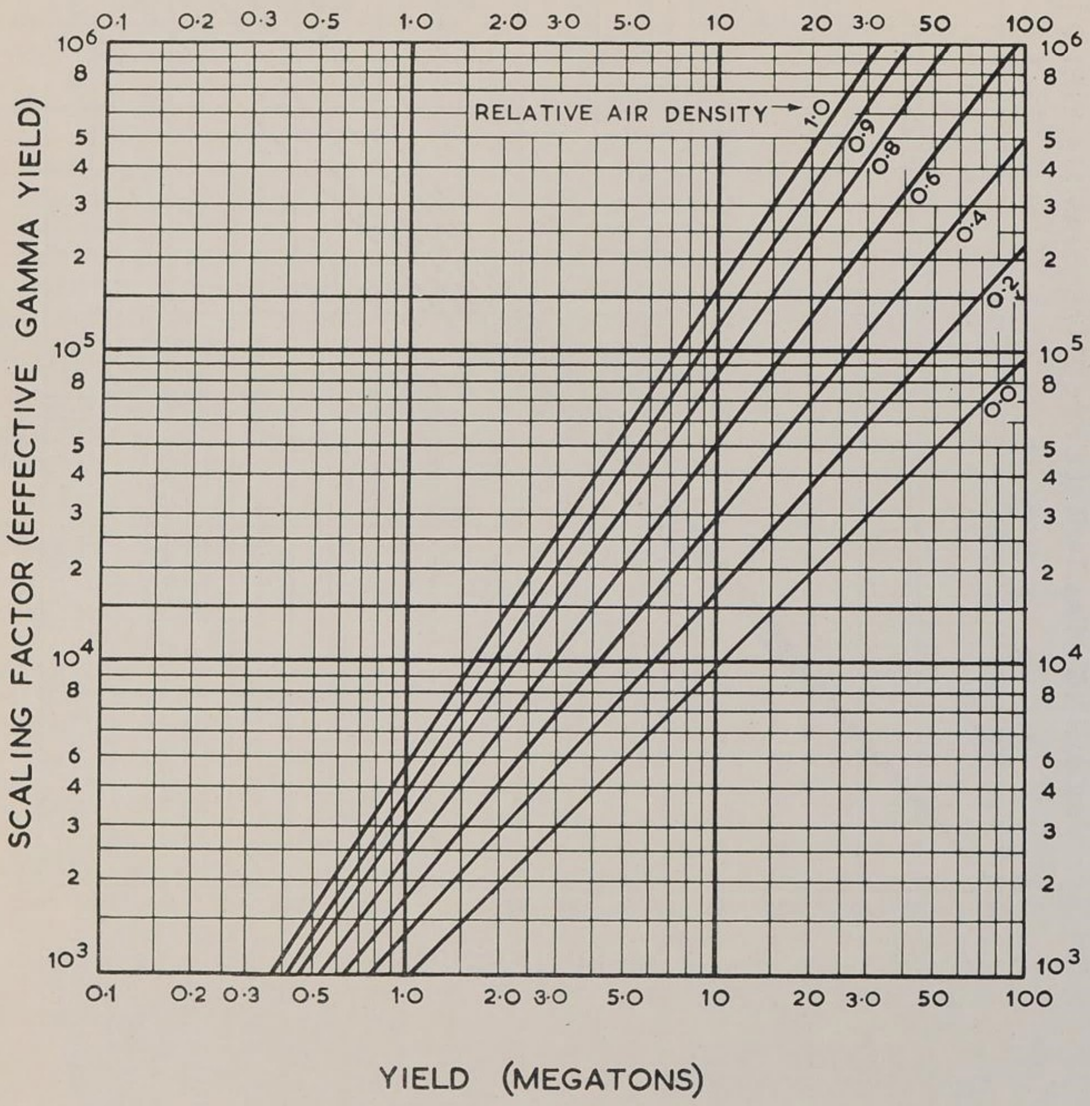
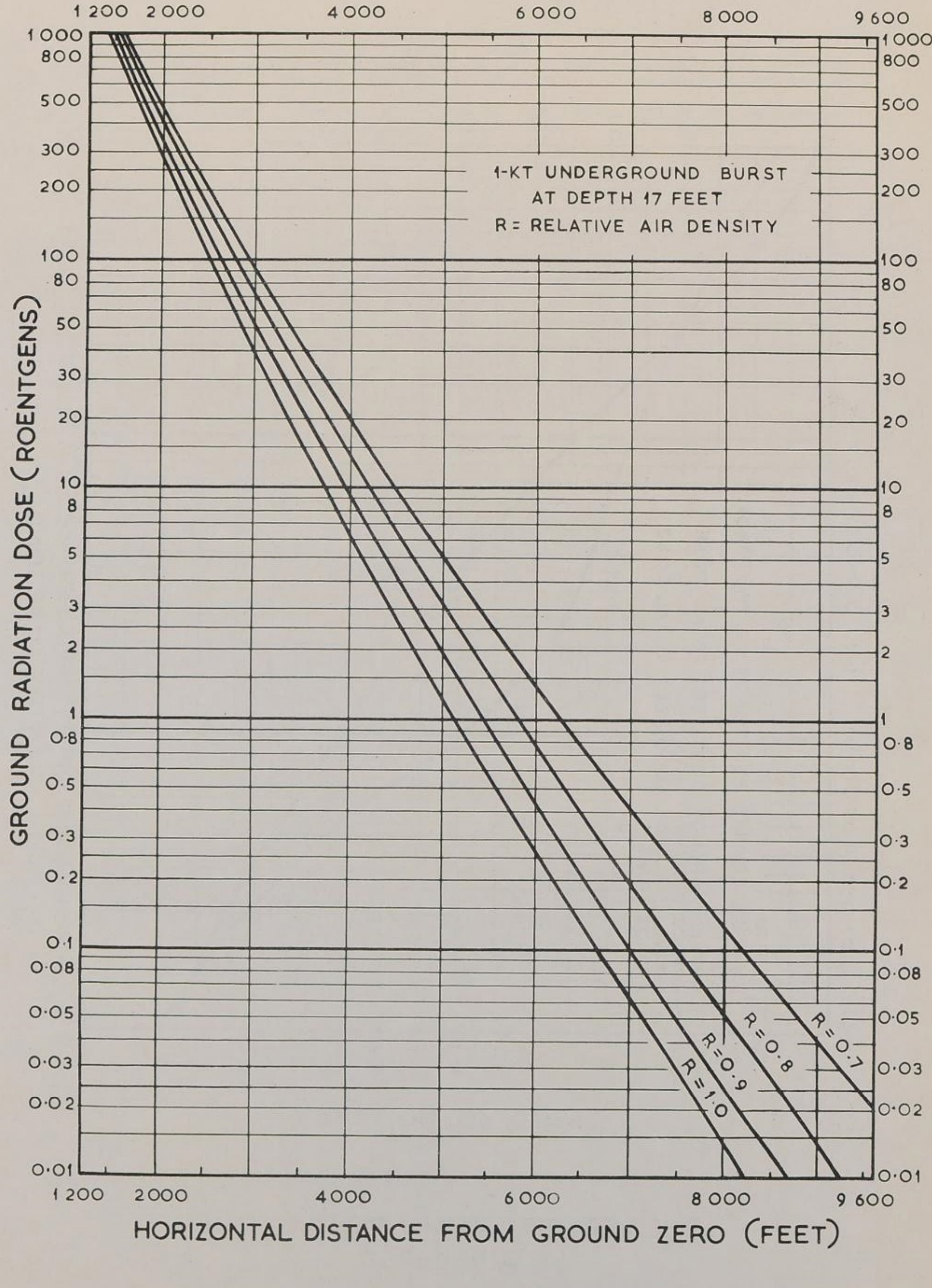


SCALING OF INITIAL GAMMA RADIATION
WITH YIELD



INITIAL GAMMA DOSE/DISTANCE CURVES FOR
1-KT UNDERGROUND BURST

PART VII
CHAPTER 3
SECTION 3.1
FIGURE 4

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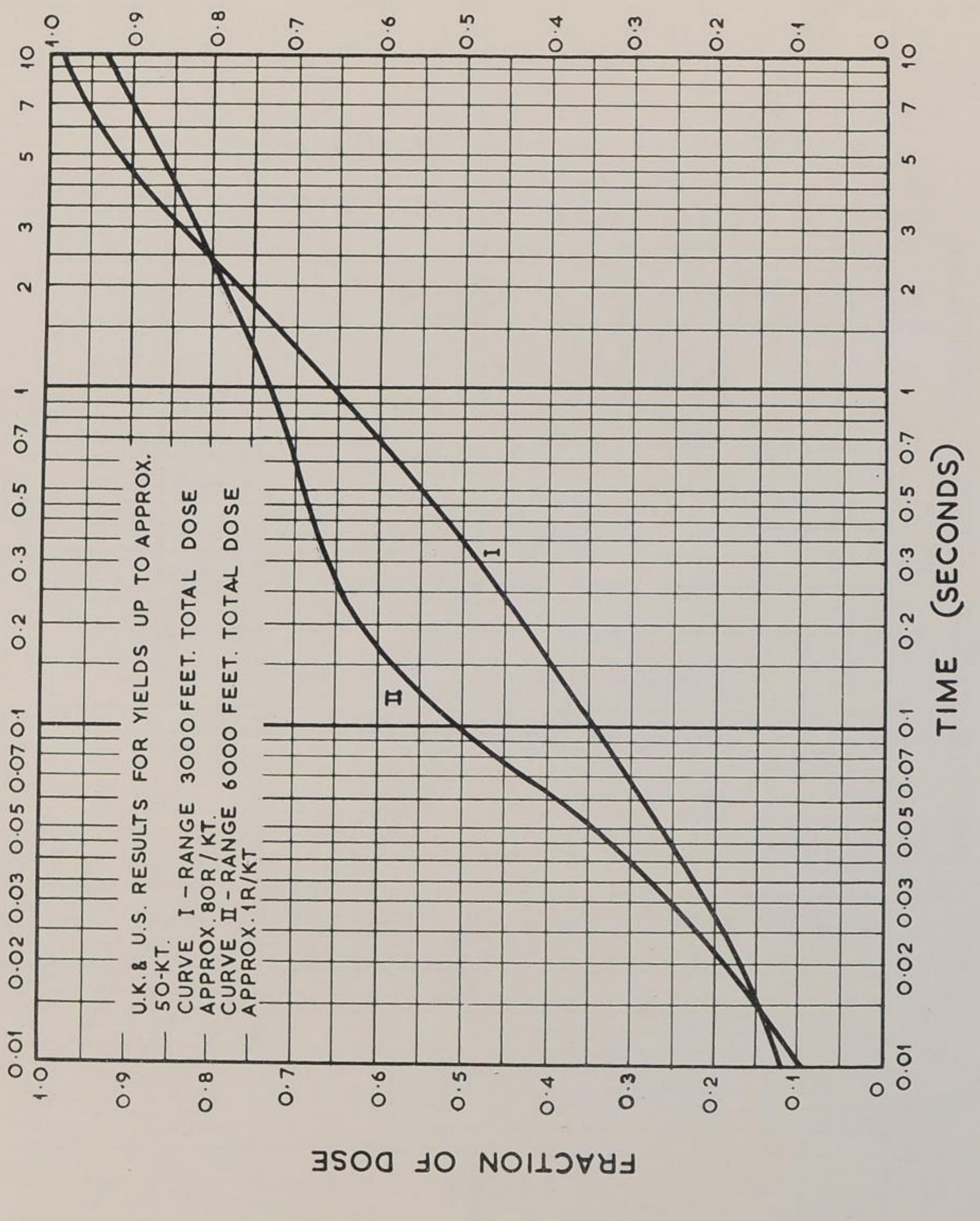
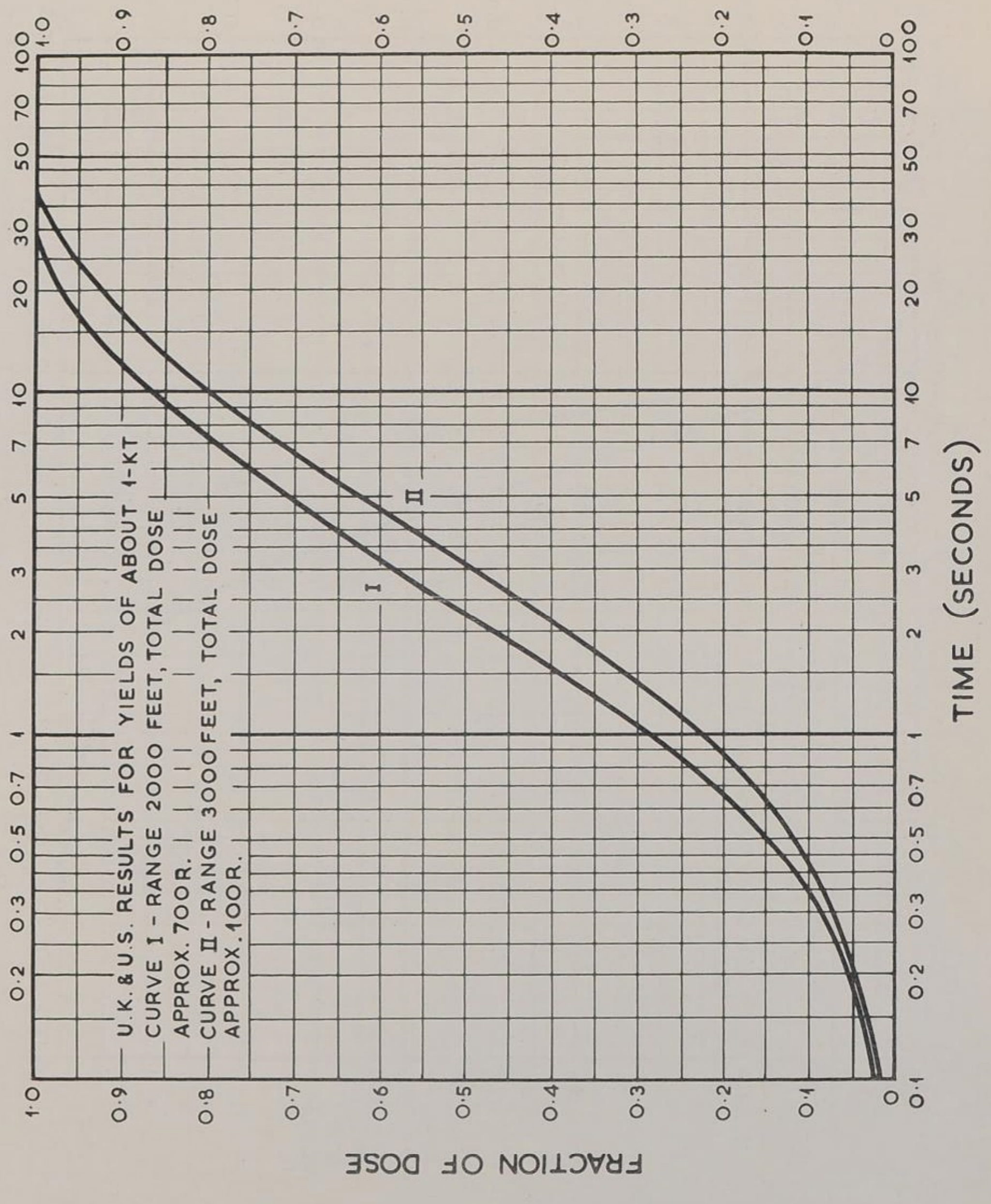


DELIVERY OF GAMMA DOSE IN TIME
AIR BURST



DELIVERY OF GAMMA DOSE IN TIME
SURFACE BURST

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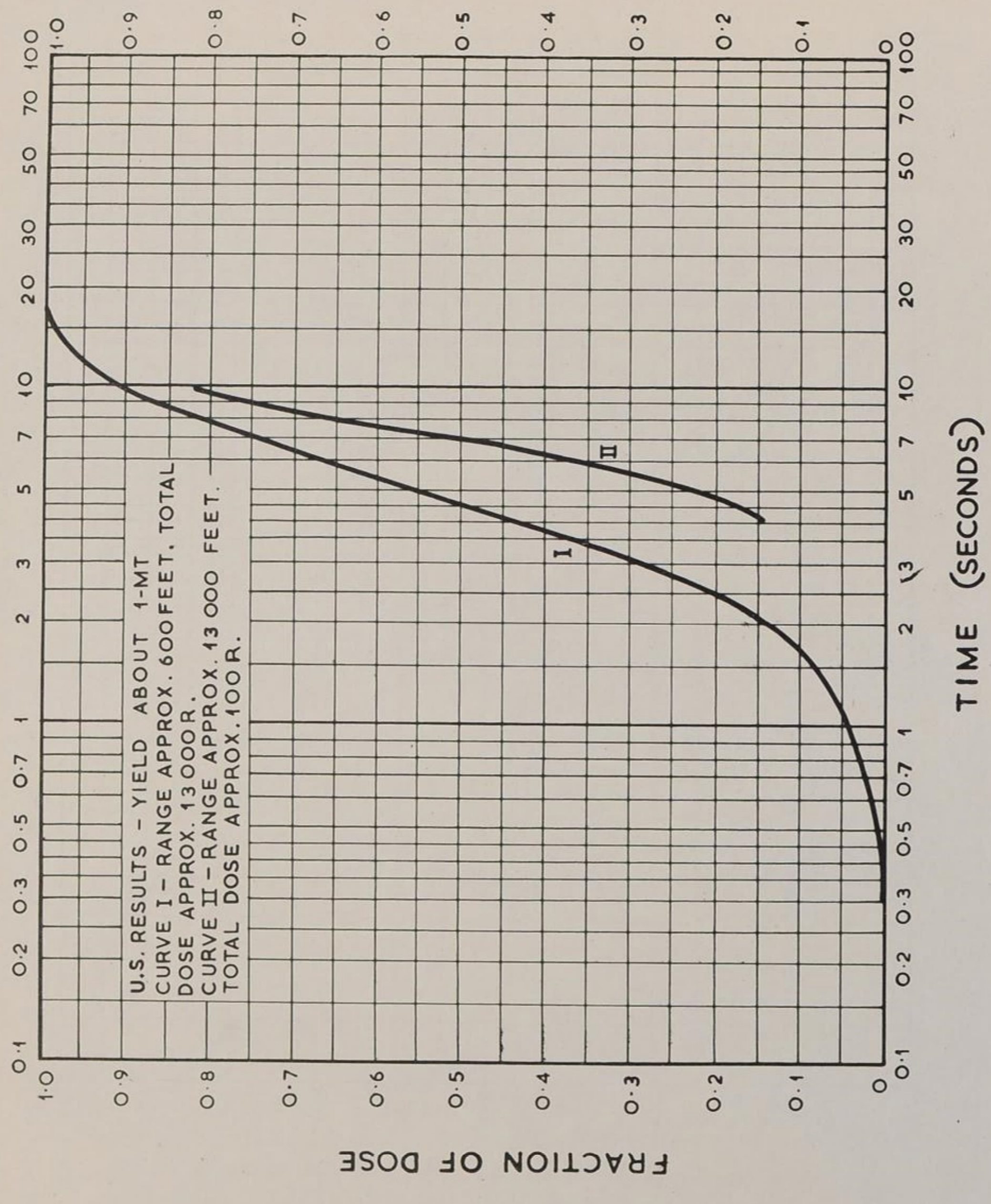
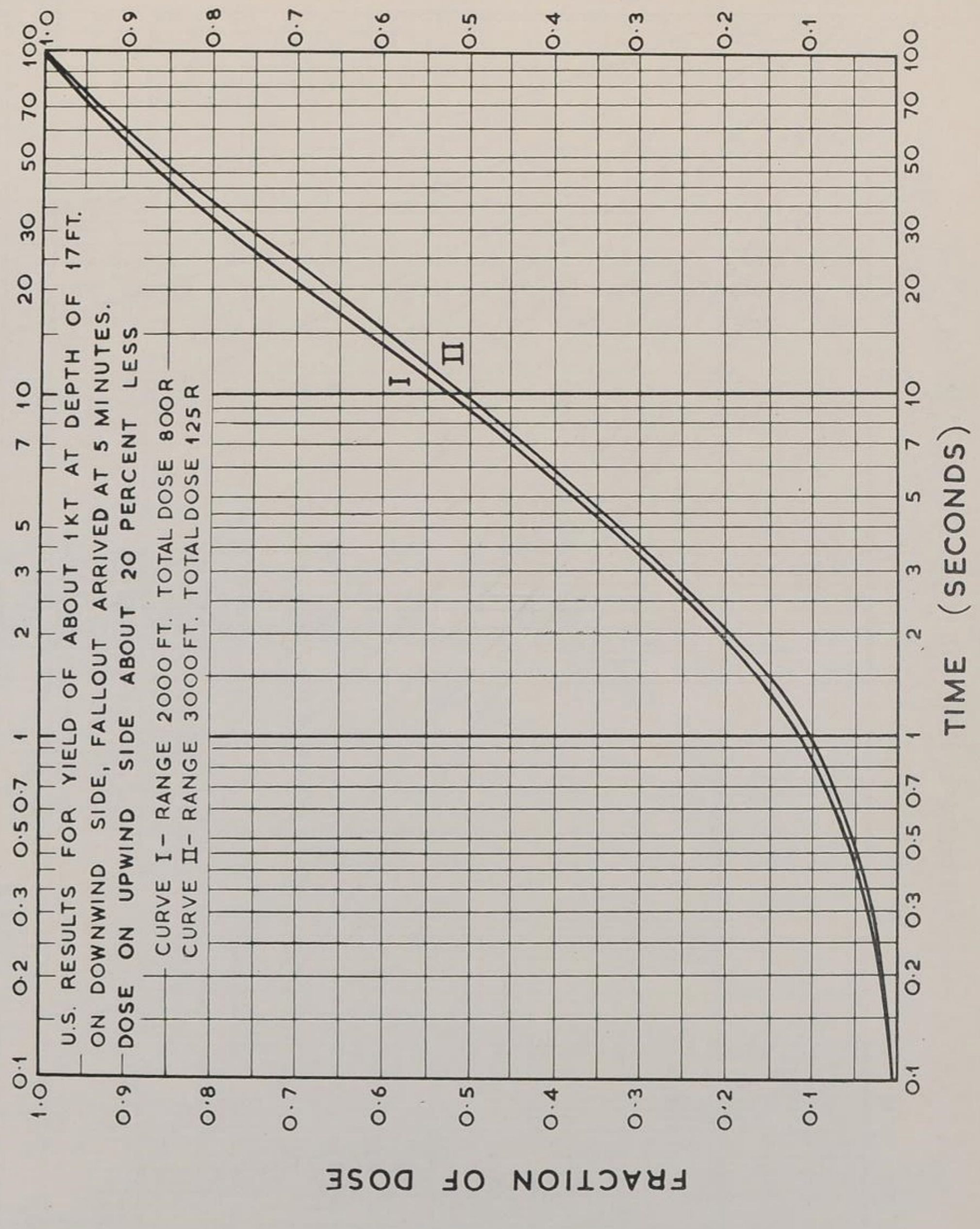


DELIVERY OF GAMMA DOSE IN TIME
HIGH YIELD SURFACE BURST



DELIVERY OF GAMMA DOSE IN TIME
SUB - SURFACE BURST

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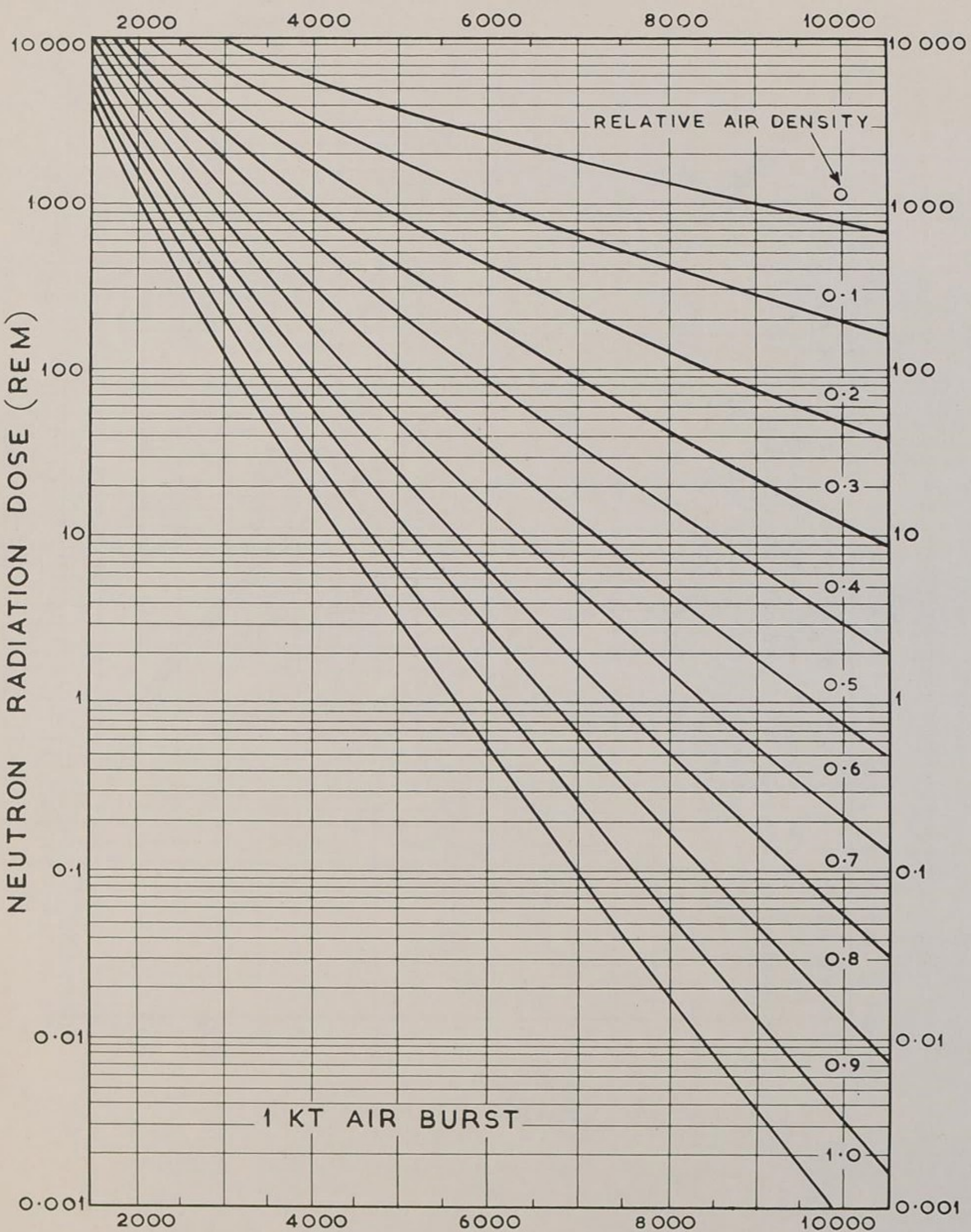
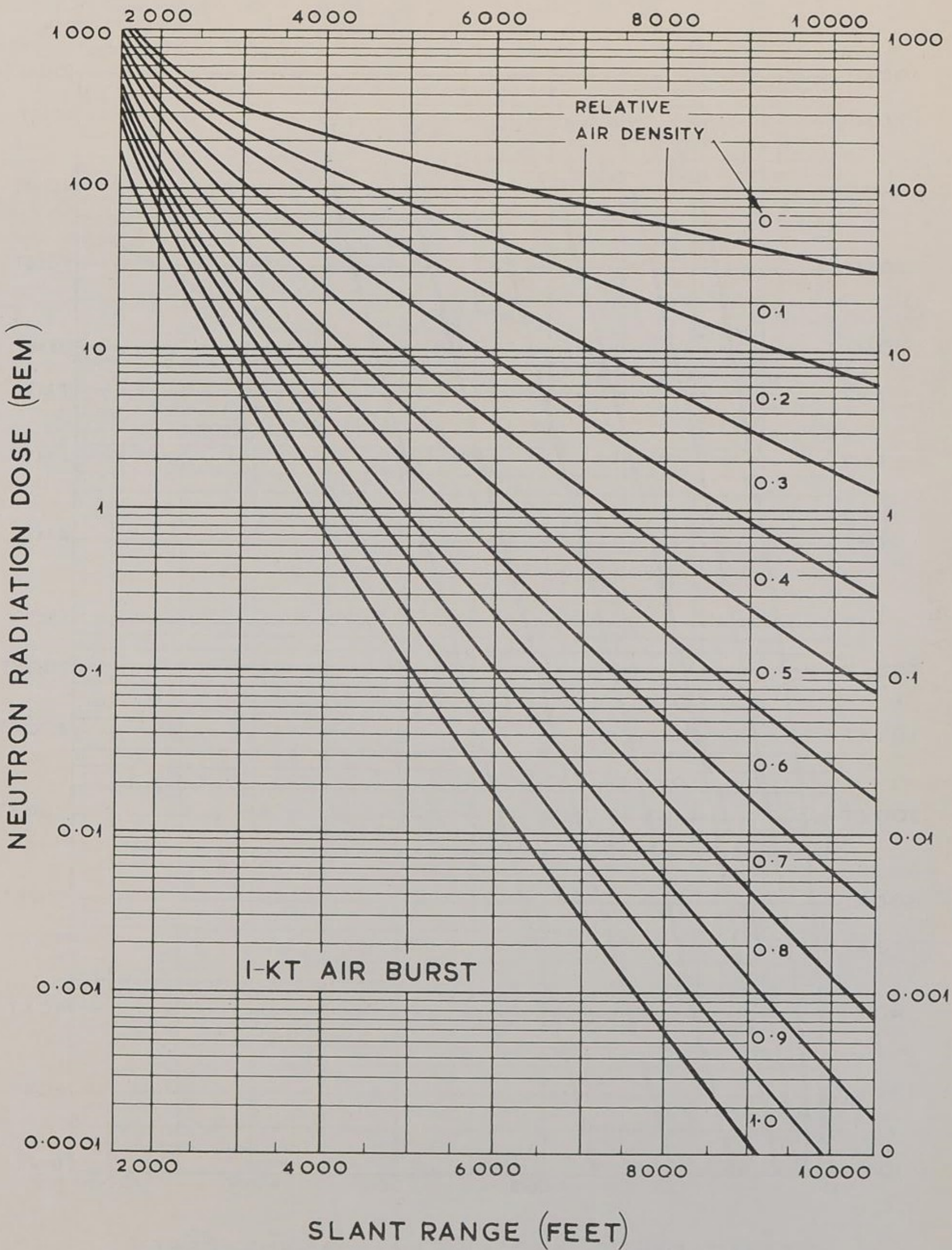


NEUTRON RADIATION DOSE AS A FUNCTION OF SLANT RANGE (HIGH NEUTRON FLUX WEAPONS)



NEUTRON RADIATION DOSE AS A FUNCTION OF SLANT RANGE (LOW NEUTRON FLUX WEAPONS)

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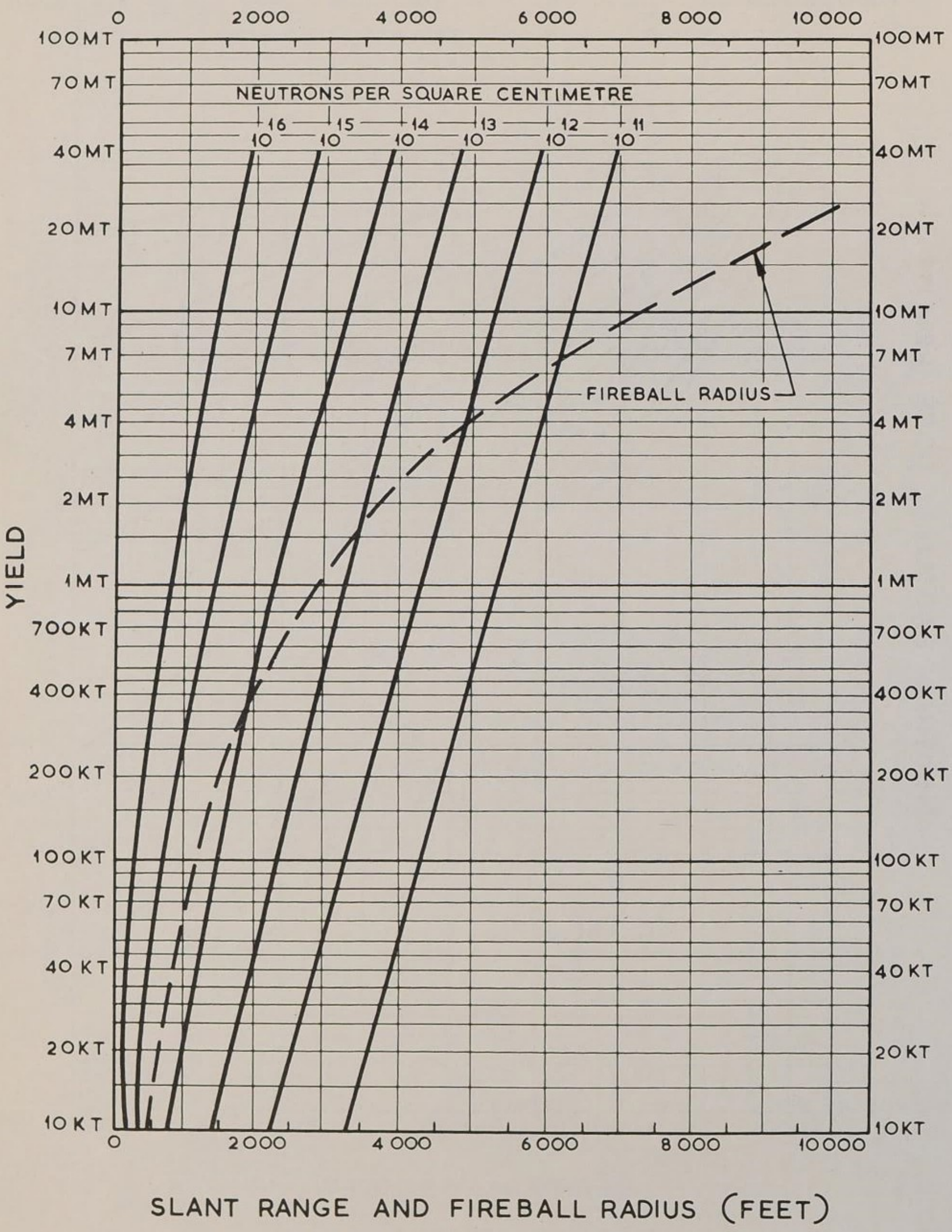

FREE AIR NEUTRON FLUX

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3.2 External Residual Radiations

Residual nuclear radiations are defined as those emitted after one minute from the time of burst of an atomic explosion. They arise from three sources:-

(a) fission products from the explosion;
(b) uranium or plutonium which has escaped fission in the explosion;
(c) activity induced by neutrons in elements present in the earth or sea.

In the case of a high air burst weapon the residual radiations would arise mainly from fission product activity, but a very low or surface burst would cause significant neutron-induced activity at the surface, as well as additional fallout from the material carried up from the surface.

The distribution of contamination from fallout is fully treated in Chapter 7, but it may be said here that in the case of a high air burst the bomb cloud carries nearly all the radioactive bomb debris to high altitudes and by the time this material falls back to earth dilution and radioactive decay will have decreased the activity to a very low level. An exception may occur in the case of a small yield weapon burst in the rain. For yields of about 8 KT and below, rain-out of radioactive material can be a hazard to personnel situated downwind and outside the danger area of initial radiations and other effects. Although weapons of greater yield produce more radioactive material, the more powerful up-currents take the bulk of this material up to an altitude above the level of precipitation.

For a surface burst the fallout in the vicinity of the explosion is a considerable hazard, as roughly half the total residual radioactivity will be deposited on the ground within a few hundred miles of the burst point.

Figure 1 gives the total radiation dose received in a contaminated area as a function of time, Reference (1). This is usually considered a gamma hazard, the associated beta hazard being normally negligible, except in the case of a person lying on contaminated ground. When much of the relatively penetrating gamma radiation is screened, e.g. by earth or buildings, a higher proportion of the dose received at a given point may be from local beta activity. Under such conditions, Radiac survey meters may give misleading under-estimates of the local dose rate if they are of the type which is sensitive only to gamma radiation (see Chapter 9, Section 9.3).

Figure 2 relates fission product decay factors with time after the explosion (Reference (1)). For example, if the dose rate at one hour after the explosion is known, the rate at any other time may be calculated. Alternatively, the decay curve may be used to determine the value of the dose rate at one hour, from the rate at a later time. See also References (2) and (3) for further details.

A useful method for determining the age of fission products is illustrated in Figure 3, (Reference (4)).

Figure 4 gives the neutron-induced gamma activity at Ground Zero for air burst weapons of various types, at a reference time of one hour after a burst of 1 KT yield, Reference (1). The activity induced, and the decay rate, will vary according to the soil composition.

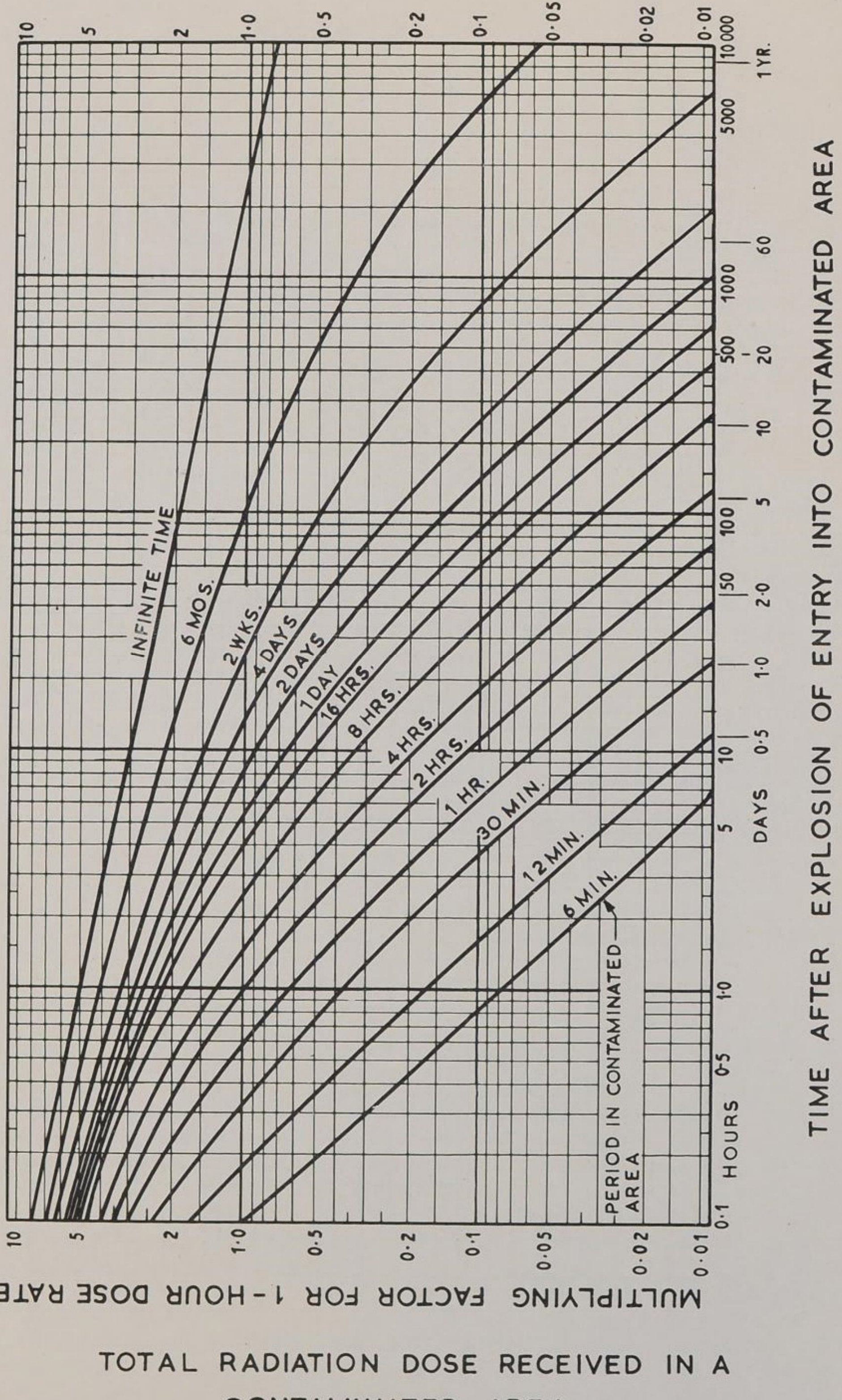
This induced activity is influenced most strongly by the sodium content of the soil, the sodium being converted by neutrons to radioactive Na^{24}, which has a half-life of 14.8 hours. This isotope emits beta particles with average energy about 0.5 Mev and gamma ray photons of 1.4 and 2.8 Mev energy.

Another source of induced activity is manganese which, being an element that is essential for plant growth, is found in most soils, even though in small proportions. As a result of neutron capture the radio-isotope Mn^{56}, with a half-life of 2.6 hours, is formed. It gives off several gamma rays of high energy, and also beta particles. Mn^{56} loses its activity more rapidly than Na^{24}, but during the first few hours after an explosion, the manganese may constitute a more serious hazard than sodium. Aluminium, a common constituent of soil, can form the isotope Al^{28}, but since its half-life is only 2.4 minutes, very little remains one hour after the explosion. Sea water contains about 3 per cent sodium chloride, and an atomic explosion near to the surface or under water will produce substantial quantities of Sodium-24. Also formed is a radio-isotope of chlorine, Cl^{38}, which has a half-life of 38.5 minutes.

Neutrons from a nuclear explosion may also be captured by nuclei contained in structural and other materials. Among the metals, the chief sources of induced radioactivity are probably zinc, copper and manganese, the latter being a constituent of many steels, and, to a lesser extent, iron. Wood and clothing are unlikely to develop appreciable activity, but glass could become radioactive because of its large sodium and silicon content. Foodstuffs can acquire induced activity, mainly as a result of neutron capture by sodium. However, at distances from a nuclear explosion at which this activity would be significant the food would probably not be fit for consumption on account of fire and blast damage. (Further details on this subject are given in Section 3.3 of this Chapter).

References

(1) Capabilities of Atomic Weapons, A.F.S.W.P. TM23-200 (1955) (Confidential/Atomic)
(2) A.W.R.E. Report No. 0-35/56(X) - "Dose Rates from Ground Contaminated with Residual Radioactive Materials from an Atomic Explosion" (Official Use Only)
(3) Radiology, Vol. 66, pp 585-94, April, 1956 - "Criteria for Evaluating Gamma Radiation Exposures from Fallout Following Nuclear Detonations" by G. M. Dunning.
(4) U.S. Air Force Special Weapons Centre. Report AFSWC-TN-56-2, (1956)



TOTAL RADIATION DOSE RECEIVED IN A CONTAMINATED AREA

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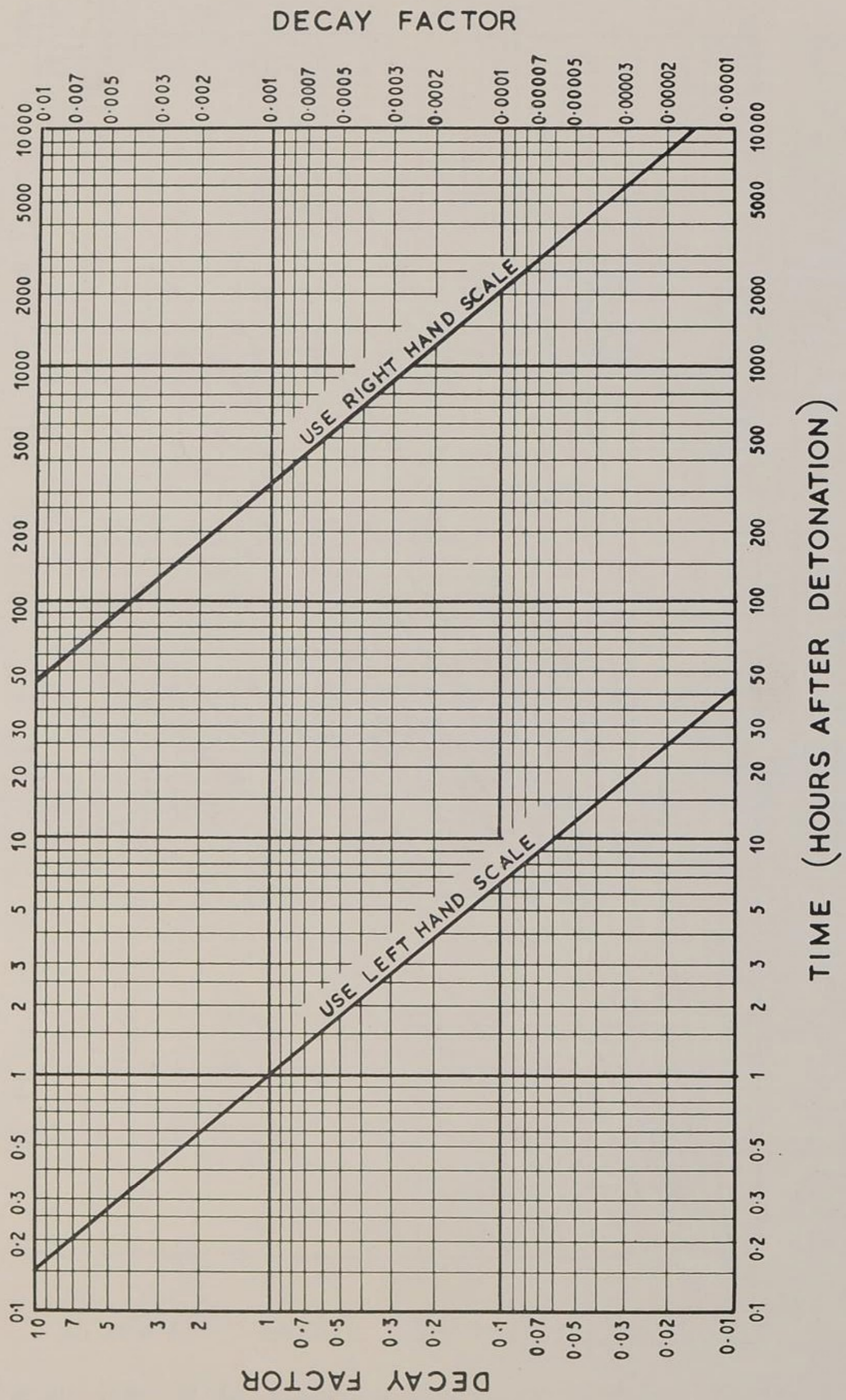

FISSION PRODUCT DECAY FACTORS FROM ONE HOUR AFTER DETONATION

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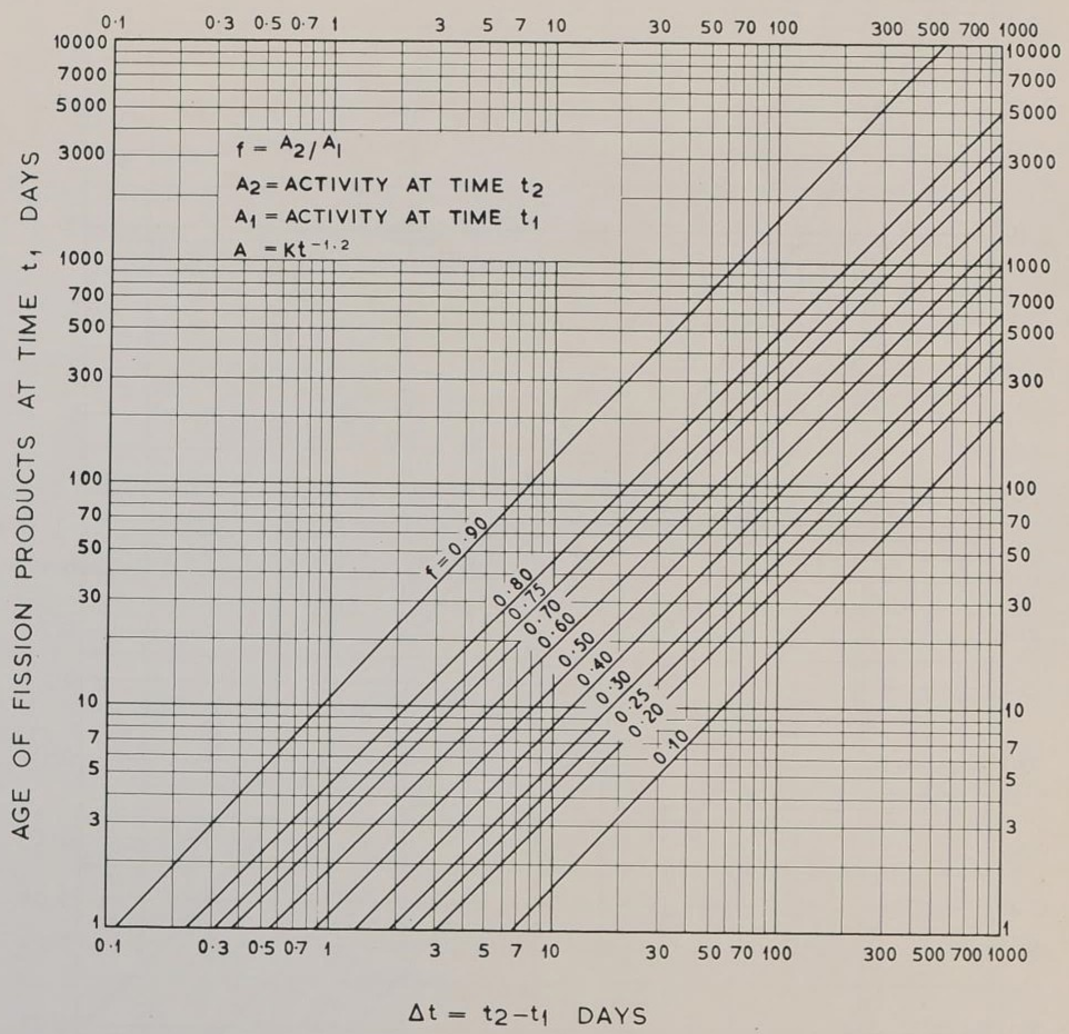

CALCULATION OF THE AGE OF FISSION PRODUCTS

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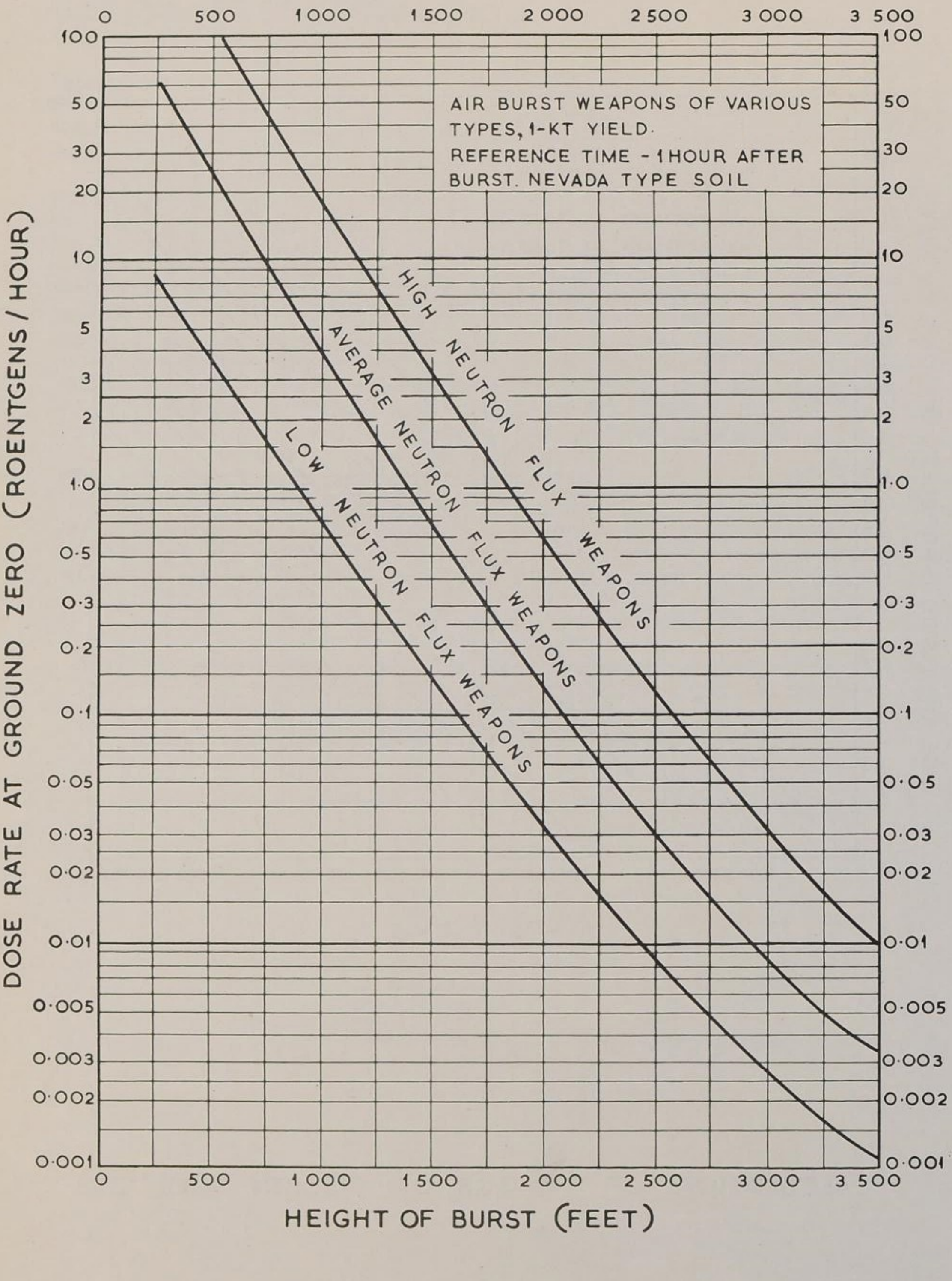


NEUTRON-INDUCED GAMMA ACTIVITY AT GROUND ZERO

3.3. Internal Irradiation

Wherever fallout occurs there is a possibility that radioactive material will enter the body through the digestive tract (due to the consumption of food and water contaminated with fission products), through the lungs (by breathing air containing fallout particles), or through wounds or abrasions. The general biological effects of nuclear radiations from internally deposited sources are the same as those from external sources. It should be noted however, that even a very small quantity of radioactive material, and especially of alpha or beta particle emitters, in the body can produce considerable injury.

The chemical properties of the fallout material which enters the body will determine where it is deposited. Radioactive elements will follow the same absorption process as their naturally occurring isotopes, and elements not usually present in the body will tend to be taken up along with normally ingested elements of similar chemical behaviour. Thus radium, strontium and barium, which are chemically analogous to calcium, will be deposited in the bone.

Unless a radioactive substance is able to pass from the stomach and intestines into the blood stream it is not strictly an internal hazard, and the quantity of the substance absorbed from the gastro-intestinal tract will depend on its solubility in body fluids, particle size, and chemical properties. For example, some fission product materials exist as oxides which are almost insoluble in the body. The oxides of strontium and barium are soluble, so that these elements can readily enter the blood stream and find their way into the bones. Iodine is also present in soluble form, and after entering the blood is concentrated in the thyroid gland. Elements which do not tend to concentrate in a particular part of the system are eleminated fairly rapidly by natural processes.

The uptake of radioactive dust by inhalation depends on the size and chemical nature of the particles. The nose can filter out almost all particles over 10 microns in diameter, and about 95 percent of those exceeding 5 microns. Most of the particles descending in the fallout during the critical period of highest activity, e.g. within 24 hours of the explosion, will be considerably greater than 10 microns in diameter. Consequently, only a small proportion of the fallout particles present in the air will succeed in reaching the lungs. Further, the optimum size for passage from the air space of the lungs to the blood stream is less than 5 microns. The probability of entry into the circulating blood of fission products and other bomb residues present in fallout, as a result of inhalation, is therefore low.

Radioactive material entering thebody through abrasions or wounds has easy access to the blood stream and can rapidly become a serious internal radiation hazard. It is therefore important that where contaimination from fallout is suspected, wounds should be carefully washed and covered.

In addition to the tendency of a particular element to be taken up selectively by a radio-sensitive organ, the main factor in determining the hazard from a given radioactive substance in the body is the total biological dose delivered whilst it is in the body. This dose is governed by the nature and energy of the radiations emitted and the effective half-life of the isotope. The isotopes having the greatest potential internal hazard are those with short radioactive half-lives (i.e. high rate of particle emission) and long biological half-lives. For example, the element iodine has a biological half-life of about 180 days, because it is quickly taken up by the thyroid gland from which it is eliminated slowly. The radioisotope I-131, a fairly common fission product, has a radioactive half-life of only 8 days. It is therefore capable of causing serious damage to the thyroid gland.

In assessing the internal hazard from a radioactive substance it is important to know the maximum permissible total-body-burden (Symbol - q). This is the quantity of radioactive material which can be retained in the body indefinitely without causing injury or ill-health. In giving values for q it is usual to allow a safety factor of 10, i.e. so that a dose of 10q would produce no ill effects. For a dose of 20-30q some chance of injury would be present, and for a dose of (say) 50q, the danger would be considerable. It is convenient to express the maximum permissible total-body-burden in curies (or microucuries) as well as by its weight in grams. The International Commission on Radiological Protection has recommended (Reference (1)) values for q for a large number of radioactive nuclides, and some of these values are quoted in Table 1.

The I.C.R.P. has also recommended values for the Maximum Permissible Concentrations (MPC) for radioactive nuclides in air and water. The MPC value is arrived at in the following way. A person using for very long periods air or water contaminated with a radioactive nuclide at a concentration equal to the MPC will accumulate a quantity of that nuclide in the relevant body-organ such that it will receive an average dose of 0.3 rem per week. The MPC values for some of the more important radioactive elements are given in Table 1.

It should be noted that except in the case of radium direct clinical evidence for the ICRP recommendations does not exist, and in some cases the q values, which are very conservatively chosen, may be considerably in error.

Standards for protection against radiation have also been compiled in the U.S.A. (Reference (2)). The Code gives recommended permissible doses, levels and concentrations, and also covers precautionary procedures and waste disposal.

An attempt to determine the degree of contamination of foodstuffs which could be accepted, and to set out the factors involved in deciding as to the usability of foodstuffs, is made in Reference (3). Permissible doses are discussed, and it is suggested that for specific isotopes a dose of 25 rep during the half-life of the isotope might be acceptable in emergency. For the fission products as a whole a total dose of 25r to the critical part of the gastro-intestinal tract is suggested. It is shown that for times earlier than about six months after the explosion, the gastro-intestinal tract is the critical organ.

The effects of neutron and gamma irradiation upon foodstuffs are reported in Reference (4). A wide variety of packaged and tinned foods were placed at four sites at distances ranging from 1,000 to 1,800 ft. from Ground Zero of Buffalo Round I, (Approximately 20KT). It was observed that it was possible for these foodstuffs to survive in conditions where neutron and gamma irradiation from the atomic explosion predominated over the heat and blast effects. Under the conditions of the experiment, negligible changes in the quality of the food were found, with the exception of deleterious effects on skimmed dried milk.

The activity induced in both the foods and in samples of spectrographically pure chemicals was evaluated, and calculations made to assess the possible radiation hazards from ingestion. It was concluded that even for the nearest site the ingestion hazard was very slight and that phosphorous made the maximum contribution to this hazard. The salvage of foodstuffs from an area near Ground Zero of a nuclear explosion may thus be possible and would not be contra-indicated by any induced radioactivity in the food or by deleterious changes in its quality.

TABLE 1

Maximum Permissible Total-Body-Burden (q) and Maximum Permissible Concentration (MPC) in Air and Water for Continuous Exposure

(Based on Recommendations of the I.C.R.P. 1954)

Radioactive Species	Radiation Emitted	Energy of Radiation Emitted (Mev)	Critical Organ	q Micro-Curies	MPC in Air Microcuries per cc	MPC in Water Microcuries per cc
H3 (HTO or T_2O)	Beta	0.018	Whole body	10^4	10^{-5}	0.2
C14(CO_2)	Beta	0.155	Fat	260	10^{-5}	3×10^{-3}
Na24	Beta Gamma	1.39 1.37, 2.75	Whole body	15	2×10^{-6}	8×10^{-3}
P32	Beta	1.701	Bone	10	10^{-7}	2×10^{-4}
S35	Beta	0.168	Skin	300	10^{-6}	5×10^{-3}
Cl36	Beta	0.714	Whole body	230	6×10^{-7}	4×10^{-3}
Fe 55	Gamma (Electron Capture)		Blood	10^3	7×10^{-7}	5×10^{-3}
Fe59	Beta Gamma	0.460 0.257 1.295, 1.10	Blood	13	2×10^{-8}	10^{-4}
Sr90+Y90 (i)Sr90 (ii)Y90	 Beta Beta	 0.61 2.2	Bone	1	2×10^{-10}	8×10^{-7}
I 131	Beta Gamma	0.608, 0.335 and others 0.364, 0.638 and others	Thyroid	0.6	6×10^{-9}	6×10^{-5}
Ra226	Alpha Gamma	4.777 0.186	Bone	0.1	8×10^{-12}	4×10^{-8}
Pu239 Soluble Insoluble	Alpha Gamma	5.15 0.053, 0.100 and others	 Bone Lungs	 0.04 0.02	 2×10^{-12} 2×10^{-12}	6×10^{-6}
Any mixture of Alpha Emitters					5×10^{-12}	10^{-7}
Any fission mixture					10^{-9}	10^{-7}

Acceptable emergency beta (or gamma) activities in drinking water, for limited periods of consumption, are given in Table 2, taken from Reference (5), page 535.

TABLE 2

Acceptable Emergency Beta (or Gamma) Activities in Drinking Water

Consumption Period (days)	Activity: Microcuries per cc	Activity: Disintegrations per second per cc
10	9×10^{-2}	3×10^{3}
30	3×10^{-2}	1×10^{3}

The emergency limits for alpha particle emitters, such as uranium and plutonium, in water are appreciably less than those given in Table 2. However, it is expected that only in rare circumstances would these elements represent a contamination hazard in drinking water.

An assessment of the hazards from the inhalation of radioactive dust from a nuclear explosion is given in Reference (6). Numerous pertinent physical and physiological factors are considered, and field and laboratory investigations analysed. It is concluded that there is no conceivable situation in nuclear warfare where, during the first few days after a detonation, one could inhale sufficient radioactive material to induce a serious radiation injury to lungs or intestines without simultaneously being subjected to supralethal doses of external beta and gamma radiations.

References

(1) Recommendations of the International Commission on Radiological Protection. British Journal of Radiology, Supplement No. 6, 1955.

(2) U.S. Code of Federal Regulations No. 10 (10 CFR), Part 20. "Standards for Protection against Radiation".

(3) A.W.R.E. Report No. O-34/56 - "Ingestion of Food Contaminated by Atomic Explosions". (Official Use Only)

(4) A.W.R.E. Report No. T65/57, Operation Buffalo, Biology Group, Part 4B: "The Effects of Neutron and Gamma Irradiation upon Foodstuffs". (Confidential)

(5) Effects of Nuclear Weapons, U.S.A.E.C., 1957.

(6) Operation Teapot, Project 37.3, Civil Effects Test Group, U.S.A.E.C. (Official Use Only)

CHAPTER 4 - EFFECTS ON MATERIALS

Materials which are subjected to very high fluxes of nuclear radiation may undergo permanent changes of structure which are referred to as "radiation damage". Neutrons are by far the most important form of radiation able to cause this type of damage. Gamma rays are also capable of producing changes in materials, but their effect is in general transitory and trivial in comparison with that of neutrons.

A consideration of the order of magnitude of neutron emission from nuclear explosions indicates that fluxes of more than 10^{15} neutrons per sq.cm. are not normally found outside the radius of the fireball (see Figure 10, Chapter 3, Section 3.1). Additionally, except for weapons of small yield, a flux of the order of 10^{11} neutrons per sq.cm. or above will only occur inside the range of severe destruction by the weapon. Table 1 gives a brief summary of the kind of damage suffered by various materials when exposed to integrated neutron fluxes of different intensities. The information in this Table is quoted from Reference (1), which should be consulted if a more detailed treatment of the subject of radiation damage is required. A recently published book dealing with radiation effects in solids is given in Reference (2).

It is thus apparent that in general any materials near enough to a nuclear explosion to sustain radiation damage will have been severaly damaged or destroyed by blast and thermal effects. An exception might arise in the case of a target which is protected from blast and thermal radiation but not effectively shielded against nuclear radiation. This would apply particularly to photographic film and certain electronic equipment, which are more susceptible to radiation damage than ordinary structural materials. The special cases of photographic film and electronic apparatus are dealt with in Part VIII of this manual.

References

(1) Nucleonics, Vol. 14, pp 53-88 (1956) - "How Radiation Affects Materials".

(2) "Radiation Effects in Solids", G.J. Dienes & G.H. Vineyard, (Interscience Publishers, 1957).

TABLE 1

Effects of Radiation on Various Materials

Note. - The levels indicated are approximate, and the changes are in most cases at least 10 percent. The irradiation dose is in epithermal neutrons and expressed as integrated flux.

Neutrons per sq. cm.	Material	Property Change
10^{14}	Germanium Transistor*	Loss of amplification
	Glass	Colouring
10^{15}	Polytetrafluorethylene	Loss of tensile strength
	Polymethacrylate and cellulosics	Loss of tensile strength
	Water and least stable organic liquids	Gassing
10^{16}	Natural and Butyl rubber	Loss of elasticity
10^{17}	Organic liquids	Gassing of most stable ones
	Polyethylene	Loss of tensile strength
	Butyl Rubber	Large changes, softening
10^{18} to 10^{19}	Phenolic polymer	Loss of tensile strength
	Natural rubber	Large change, hardening
	Hydrocarbon oils	Increase in viscosity
	Metals	Increase in yield strength
	Carbon Steel	Reduction of notch-impact strength
	Polystyrene	Loss of tensile strength
10^{20}	Ceramics	Reduced thermal conductivity, density, crystallinity
	All plastics	Unusable as structural materials
	Carbon steels	Severe loss of ductility, yield strength doubled
	Stainless steels	Yield strength tripled
10^{21}	Aluminium alloys	Ductility reduced but not greatly impaired
	Stainless steels	Ductility reduced but not greatly impaired

*See also Part VIII of this Manual.

CHAPTER 5 - SHIELDING FROM INITIAL RADIATORS

5.1. Gamma Radiation

5.1.1. Basic principles - A description of the nature and origin of the initial gamma radiation from a nuclear weapon is given in Chapter 5 of Reference (1). An unclassified account will be found in Chapter 8 of Reference (2). In considering shielding problems, it is important to note that this gamma radiation has complicated distributions of both energy and direction and that these distributions vary with distance from the explosion and height above the earth's surface. Because of this, it is not possible in practical shielding problems to base calculations on the actual physical nature of the incident radiation.

The parameters which control the efficiency of shielding are the mass of material between the source of radiation and the target, the energy distribution of the gamma rays at the target, the angle of the incident radiation, and the geometry of the shielding. Observations made at weapon tests have enabled the calculation of attenuation factors which combine these controlling parameters. The solutions to practical shielding problems are normally obtained by the use of a simplified model and the application of appropriate attenuation factors.

References

(1) A.W.R.E. Manual on the Effects of Atomic Weapons, 1955
(Secret/Atomic/U.K. Eyes Only)

(2) Effects of Nuclear Weapons, U.S.A.E.C., 1957.

5.1.2 The interaction of gamma rays with matter

There are three types of interaction between gamma rays and matter which lead to the scattering or absorption of the gamma photons and so are of importance in considering shielding. They are:-

(a) the photoelectric effect;

(b) the Compton effect;

(c) pair production.

A brief description follows for the convenience of those not requiring a detailed treatment, such as may be found in References (1) and (2).

(a) Photoelectric effect - In this type of interaction a gamma photon with energy greater than the binding energy of an orbital electron transfers all its energy to the electron, which is then ejected with considerable energy from the atom. After such a photoelectric interaction, the photon ceases to exist. The probability of a photon being absorbed in this manner, per atom, is proportional to the fifth power of the atomic number of the material through which the gamma radiation is passing, but it decreases rapidly with increasing photon energy. Even in the case of lead this photoelectric effect is relatively unimportant above 1 Mev, and for light elements, above a few Kev.

(b) Compton effect - Here a gamma photon exhibits particle properties, and its encounter with an electron results in an elastic or 'billiard ball' collision. The photon transfers some of its energy to the electron and at the same time is deflected from its original path. The energy loss and the angle of deflection are closely related. The magnitude of this effect per atom is proportional to the number of electrons in the atom on the shielding element, and hence to its atomic number, but the effect decreases with increasing photon energy. Unlike the case of the photoelectric effect, the photon does not disappear completely after a Compton interaction, but continues in a changed direction with reduced energy and an energetic Compton electron is released.

(c) Pair production - A photon with energy greater than about 1.02 Mev may, when it passes near to an atomic nucleas, be annihilated with the production of a pair of particles, one a negative electron and one a positron. Any energy in excess of 1.02 Mev, the energy required to form the pair of particles, appears as kinetic energy of the pair. This type of interaction results in the complete disappearance of the photon. Pair production cannot occur with photon energies less than 1.02 Mev, and thereafter the probability of the effect increases with both photon energy and atomic number.

In considering the three types of interaction described above, it is seen that in all cases the magnitude per atom increases with increasing atomic number (or atomic weight) of the materials through which the gamma rays pass. Each effect too, is accompanied by either the complete removal of photons or a decrease in their energy. The net result is some attenuation of the gamma ray intensity or dose rate. Since there is an approximate parallelism between atomic weight and density, the number of atoms per unit volume does not vary greatly from one substance to another. Hence, a given volume (or thickness) of a material containing elements of high atomic weight ('heavy elements') will be more effective as a gamma shield than the same volume (or thickness) of one consisting only of elements of low atomic weight ("light elements").

Another important point is that the probabilities of the Compton and photo-electric effects (per atom) both decrease with increasing energy of the gamma photon. Combination of these various attenuating effects, two of which decrease whereas one (pair production) increases, with increasing photon energy, means that at some energy (in excess of 1.02 Mev) the absorption of gamma radiation by a particular material should be a minimum.

References

(1) The Quantum Theory of Radiation, W. Heitler, 1953.

(2) U.S. Atomic Energy Commission Report NYO 3075, by Goldstein and Wilkins.

5.1.3 Gamma radiation attenuation laws

Photons which are involved in photoelectric or pair production interactions are completely lost from the gamma ray beam. If it is assumed that photons involved in Compton encounters are also lost from the beam, the attenuation law for a parallel beam will be as follows:-

$$I = I_o e^{-\mu} \qquad (5.1.1.)$$

Where I is the intensity behind the shield,

I_o is the intensity at the same point in the absence of the shield

x is the thickness of the shield, and

μ is the absorption coefficient for the material of the shield for the gamma rays under consideration.

The total absorption coefficient μ is made up of separate coefficients, μ_{pe}, μ_c, μ_{pp}, for the three effects described above. Figure 1 gives the values of these coefficients for lead, a typical heavy element with a large absorption coefficient, and Figure 2 the values for air, a mixture of light elements withaa small absorption coefficient, Reference (1).

In the discussion so far, we have used the simplifying assumption that photons involved in Compton collisions are lost from the beam. In fact however, many photons which have been deflected and degraded in energy one or more times will arrive behind the shield and will consequently increase the intensity to a value greater than that given by Equation 5.1.1. This, the usual practical situation, is sometimes referred to as "Bad Geometry". It will be seen that even if the incident beam were homogeneous and parallel, the beam emerging behind the shield would not be so. When the radiation from a nuclear weapon is considered, even the incident beam possesses a complicated spectrum of energies and directions. In such circumstances direct calculation of shielding based on numbers of photons, their energies and directions becomes too tedious. It should be noted that the effects against which shields are established are all dependent on the energy actually absorbed within the individual or object being protected, and consequently it would be necessary to compute both the overall reduction in flux of the photons, and the degradation of their energies in order to determine the shielding effects. As the reduction in direct radiation may be offset by scattering from other parts of the shield or from other objects, and also the mean energy of the radiation may be reduced in such a way as to increase the amount actually absorbed in the object to be protected, the overall analysis is likely to be tedious. In practice the best solution is to make observations at weapon trials of the reduction of dose or dose rate (ion pairs per cc per second) in the object or simulated object behind the various shields, and then to determine an "equivalent homogeneous radiation" by one of the published approximate methods of calculation. See References (2), (3) and (4) for details.

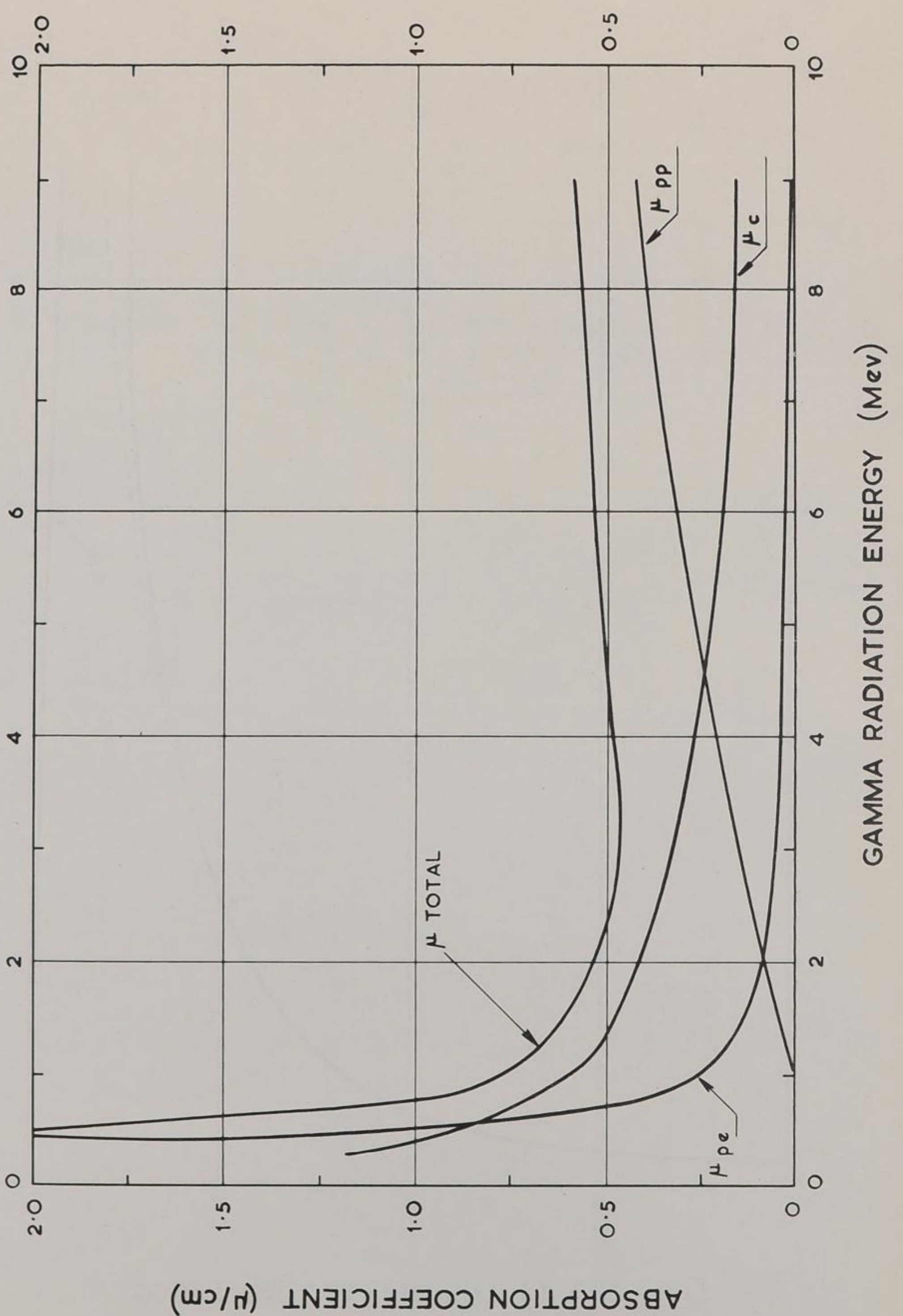
References

(1) The Effects of Nuclear Weapons, U.S.A.E.C., 1957, p. 376.

(2) Cave, Corner and Liston, Proc.Roy.Soc. Vol. A.204, p.223, 1950 "Perpendicular Incidence on a Plane Slab"

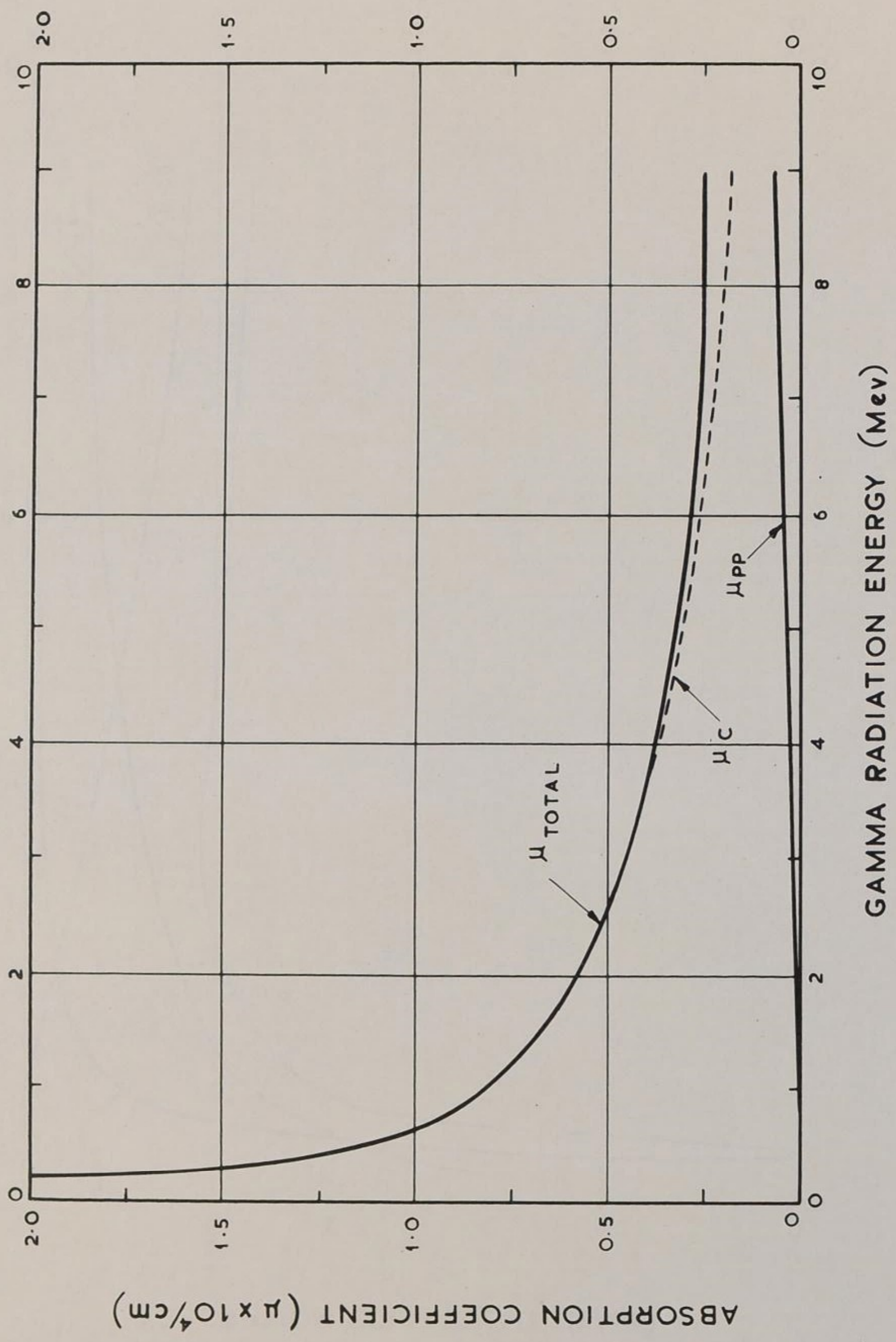
(3) Ministry of Supply, H.E.R. Report No. H13/51 (Restricted) "Tables for the Solution of Gamma Ray Shielding Problems"

(4) A.W.R.E. Report No. T53/54 (Secret) - "Penetration of Concrete Slabs by Gamma Radiation".



ABSORPTION COEFFICIENT OF LEAD FOR
GAMMA RADIATIONS

UNCLASSIFIED



ABSORPTION COEFFICIENT OF AIR FOR
GAMMA RADIATIONS

UNCLASSIFIED

5.1.4. Attenuation data for light elements

"Light elements" in this connection are elements with an atomic number less than about 30, that is, corresponding to atomic weights up to about 65 (Zinc). For such elements the preponderant mechanism of attenuation is the Compton effect.

The protective qualities of a shield can be defined by the "attenuation factor", which is the ratio of the dose immediately behind the shield to the dose which would be at that point in the absence of the shield. Methods of computing attenuation factors for simplified conditions have been described in References (1) and (2). Figure 1 is based on those methods applied to radiation beams perpendicular to a concrete shield of density 144 lb./cu.ft. (2.3 gm/cc). Equivalent thicknesses of other light element materials are inversely proportional to the density of the material. A list of densities of a number of common materials is given in Table 1.

Measurements of dose reduction by concrete shields were made at British trials of weapons in the kiloton range (Operation Totem), References (3) and (4). The results indicated a photon energy of 1 Mev used in the "modified upper limit" method of calculation (Reference (2)) to be satisfactory. For thin shields (less than about six inches of concrete) close enough to the weapon for the free air dose to be greater than 200 r, an energy of about 0.5 Mev is more realistic. Figure 1 is calculated on the "modified upper limit" formulae and therefore may be used without further calculation. More recent results from Operation Buffalo (Reference (5)) differ from those obtained at Totem, and show that the design of the weapon is the dominant factor. The penetration of gamma-rays through concrete slabs at Buffalo appeared to be consistent with exponential attenuation with a half-thickness of concrete corresponding to 51 $lb./ft.^2$. Thus the radiation appeared to be considerably harder than at Totem where the half-thickness correspond to 20-29 $lb./ft.^2$.

Figure 2, taken from Reference (6), gives attentuation factors for various materials as a function of shield thickness.

No experimental results are available for megaton weapons, but because of the probable increase in the amount of $(n.\gamma)$ radiation from nitrogen in the air it is expected that a higher energy would have to be used. Approximate calculations based on U.S. data for "free air" doses suggest about 5 Mev.

It should be noted that the absorption of neutrons in light elements is accompanied by the production of gamma radiation, of which account must be taken. References (7) and (8) give details of this.

References

(1) Cave, Corner & Liston, Proc.Roy.Soc. Vol. A.204, p.223, 1950 "Perpendicular Incidence on a Plane Slab".

(2) Ministry of Supply, H.E.R. Report No. H13/51 (Restricted) "Tables for the Solution of Gamma Ray Shielding Problems".

(3) A.W.R.E. Report No. T53/54 (Secret) - "Penetration of Concrete Slabs by Gamma Radiation".

(4) A.W.R.E. Report No. T20/54 (Secret) - "The Penetration of the Gamma Flash into Anderson Shelters and Concrete Cubicles".

(5) A.W.R.E. Report No. T42/57, Operation Buffalo. "Attenuation and Scattering of Initial Nuclear Radiations". (Secret/Atomic/U.K. Eyes Only)

(6) Effects of Nuclear Weapons, U.S.A.E.C, 1957, p.357.

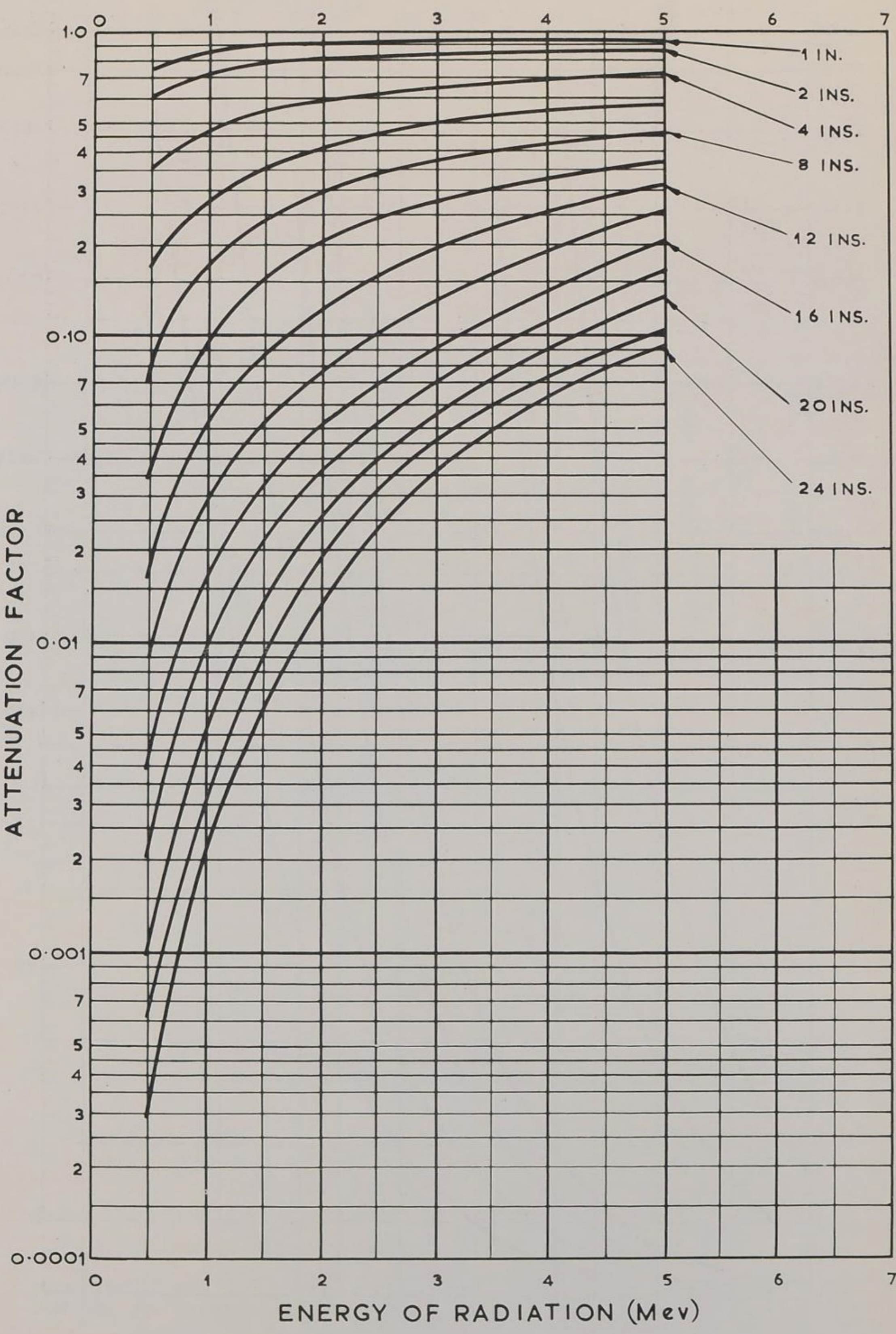
(7) Nucleonics, Vol. 13 (No.5) pp.50-51. Shielding Constants. Gamma Rays from Thermal Neutron Capture.

(8) Nucleonics, Vol. 15 (No.4) pp.84-85. Induced Radiation. Radiation from Neutron Activated Slabs and Cylinders.

TABLE 1

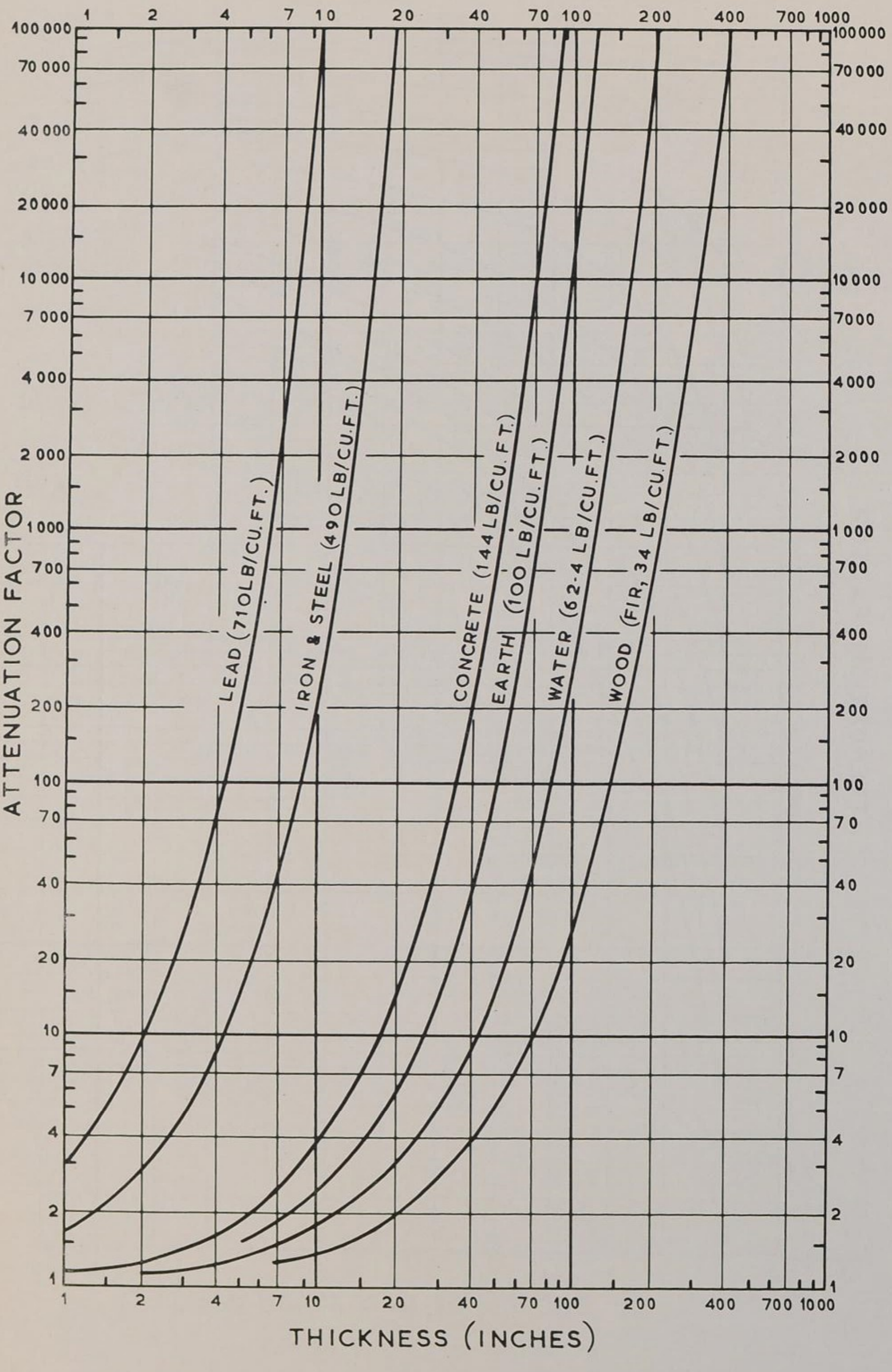
Densities of Some Common Materials

Material	Density lb./cu. ft.
Brick	120 - 140
Mortar	90 - 120
Plaster	50 - 180
Concrete	140 - 150
Reinforced concrete	140 - 190
Steel	435 - 495
Iron	450 - 480
Lead	710
Aluminium	169
Copper	550
Hardwood	40 - 55
Softwood	30 - 44
Indiarubber	58
Glass	160 - 170
Earth	77 - 120
Clay	120
Sand Wet	115 - 130
Sand Dry	90 - 110
Chalk	145
Sandstone	130 - 170
Limestone	130 - 140
Slate	160 - 180
Granite	165 - 175



ATTENUATION FACTORS FOR GAMMA RADIATION FOR LIGHT ELEMENT SHIELDS (DENSITY 144 LB. PER. CU. FT.)

UNCLASSIFIED



ATTENUATION OF INITIAL GAMMA RADIATION

UNCLASSIFIED

5.1.5 Attenuation data for heavy elements

In heavy elements (atomic number greater than about 30) photoelectric and pair production phenomena play increasingly important parts, and consequently it is not adequate to make adjustments from Figure 1 of Section 5.1.4 on a density basis only. Multiple scattering by the Compton mechanism is still important, although less so than in the case of light elements. Because of this change in the relative importance of the three main effects, the heavy elements provide generally better shields than would be expected from density considerations only. Figure 1 shows the attenuation factors for lead shields, the data having been drawn from References (1) and (2). Observations from weapon tests are not available, but the greater magnitudes of the photo-electric and pair production effects, together with the 0.5 Mev annihilation radiation from the latter effect, suggest that the energy of the equivalent homogeneous radiation should be rather lower than is the case with shields of light elements.

Some useful information regarding the properties of shields for gamma radiation may be obtained from the data sheets quoted in References (3) to (7) inclusive. By courtesy of the Publishers, these data sheets are reproduced in Figures 2 to 9.

References

(1) The Effects of Nuclear Weapons, U.S.A.E.C., 1957

(2) Ministry of Supply A.R.E. Report No. 3/54 - "The Absorption of Gamma Radiation in Lead, Steel and Concrete". (Unclassified)

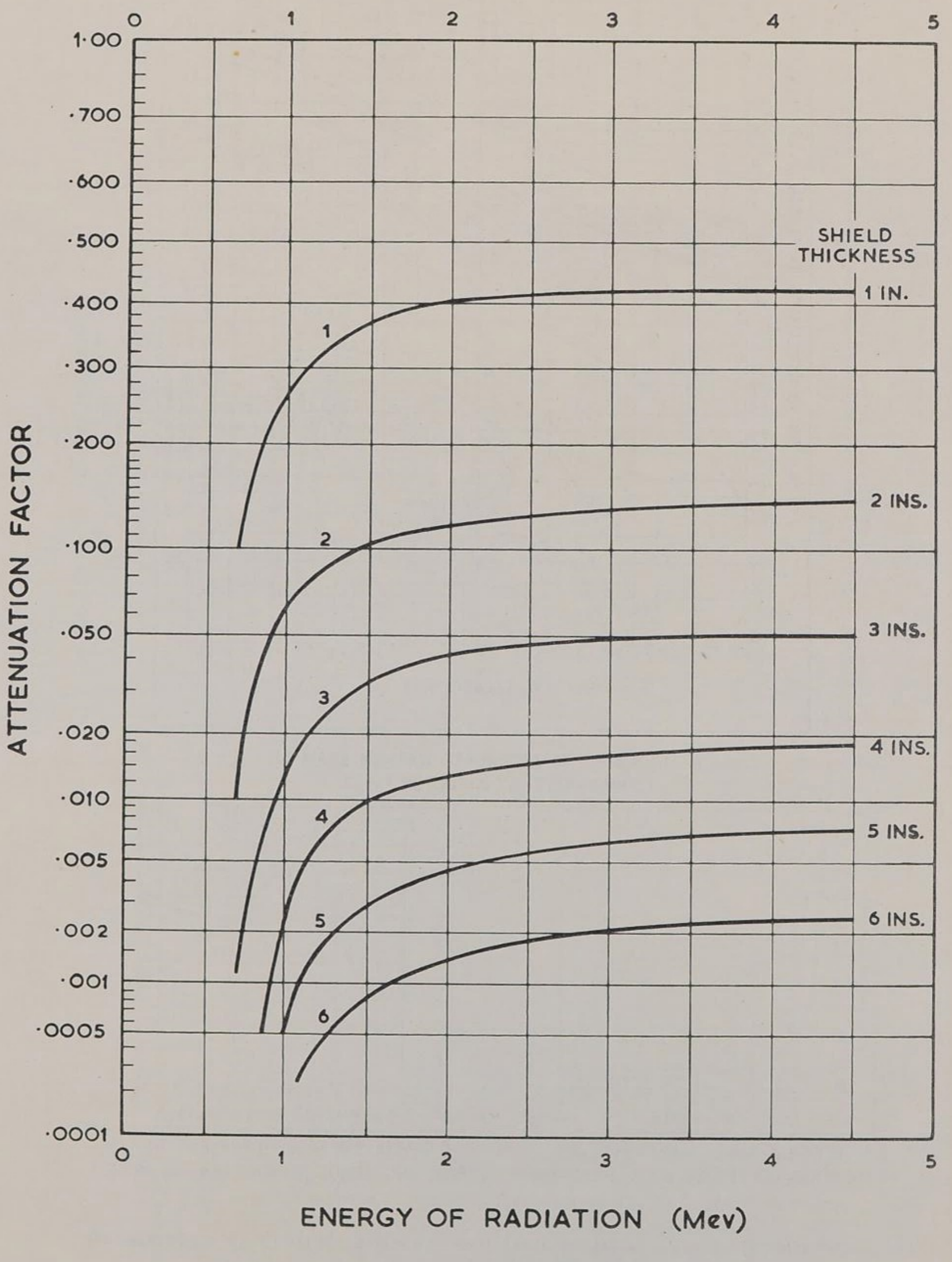
(3) Nucleonics Vol. 13 (No. 7) p.24, Data Sheet No. 5 - Shielding Constants. Tenth Value Thicknesses for Gamma Ray Absorption (0.1 - 9 Mev, Good Geometry).

(4) Nucleonics Vol. 14 (No. 1) p.40-41, Data Sheet No. 10 - Shielding Constants, Gamma Ray Attenuation (0.1 - 6 Mev).

(5) Nucleonics Vol. 14 (No. 7) pp.36-37, Data Sheet No. 14 - Shielding Constants. Gamma Ray Scattering from Thin Scatterers.

(6) Nucleonics Vol. 14 (No. 11) p.87, Data Sheet No. 16 - Shielding. Gamma Ray Streaming through an Annulus.

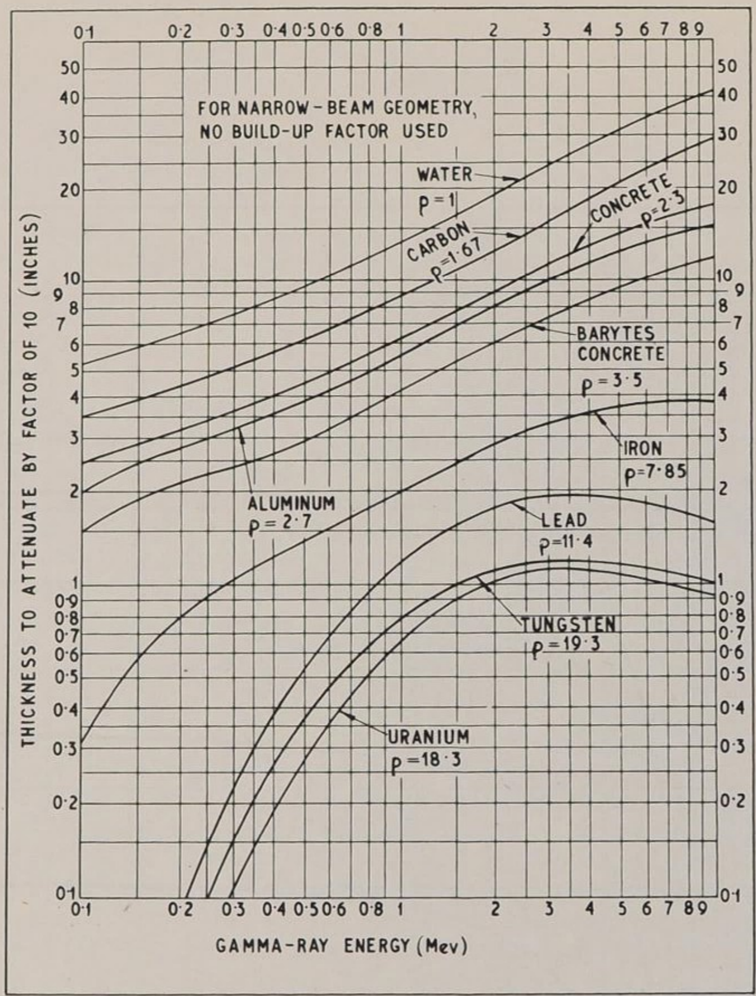
(7) Nucleonics Vol. 15 (No. 1) pp.52-53, Data Sheet No. 18 - Shielding. Gamma Attenuation with Build-up in Lead and Iron.



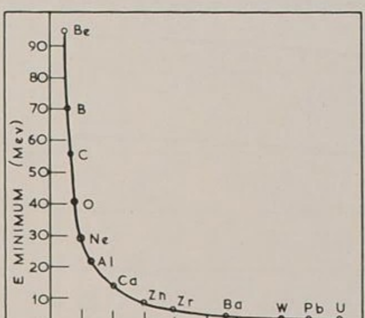
ATTENUATION FACTORS FOR GAMMA RADIATION
FOR HEAVY ELEMENT (LEAD) SHIELDS

UNCLASSIFIED

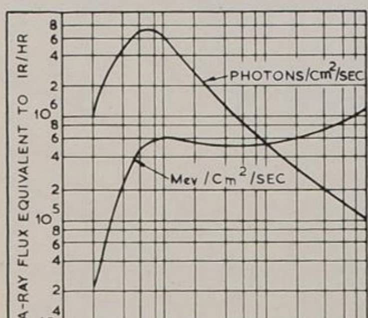
D.N.W.
JAN. 1958.



A. THICKNESS TO ATTENUATE NARROW BEAM OF GAMMA-RAYS BY A FACTOR OF 10



B. ENERGY AT WHICH NARROW-BEAM ABSORPTION COEFFICIENTS ARE A MINIMUM



C. GAMMA-RAY FLUX EQUIVALENT TO 1R/HR AS A FUNCTION OF GAMMA-RAY ENERGY

THE THICKNESS TO ATTENUATE BY A FACTOR OTHER THAN TEN MAY BE OBTAINED BY MULTIPLYING THE TENTH-VALUE THICKNESS BY THE COMMON LOGARITHM OF THE DESIRED FACTOR, E.G. HALF-VALUE THICKNESSES ARE $\log_{10} 2 = 0{\cdot}3010$ TIMES TENTH-VALUE THICKNESSES.

TENTH-VALUE THICKNESSES FOR GAMMA-RAY ABSORPTION

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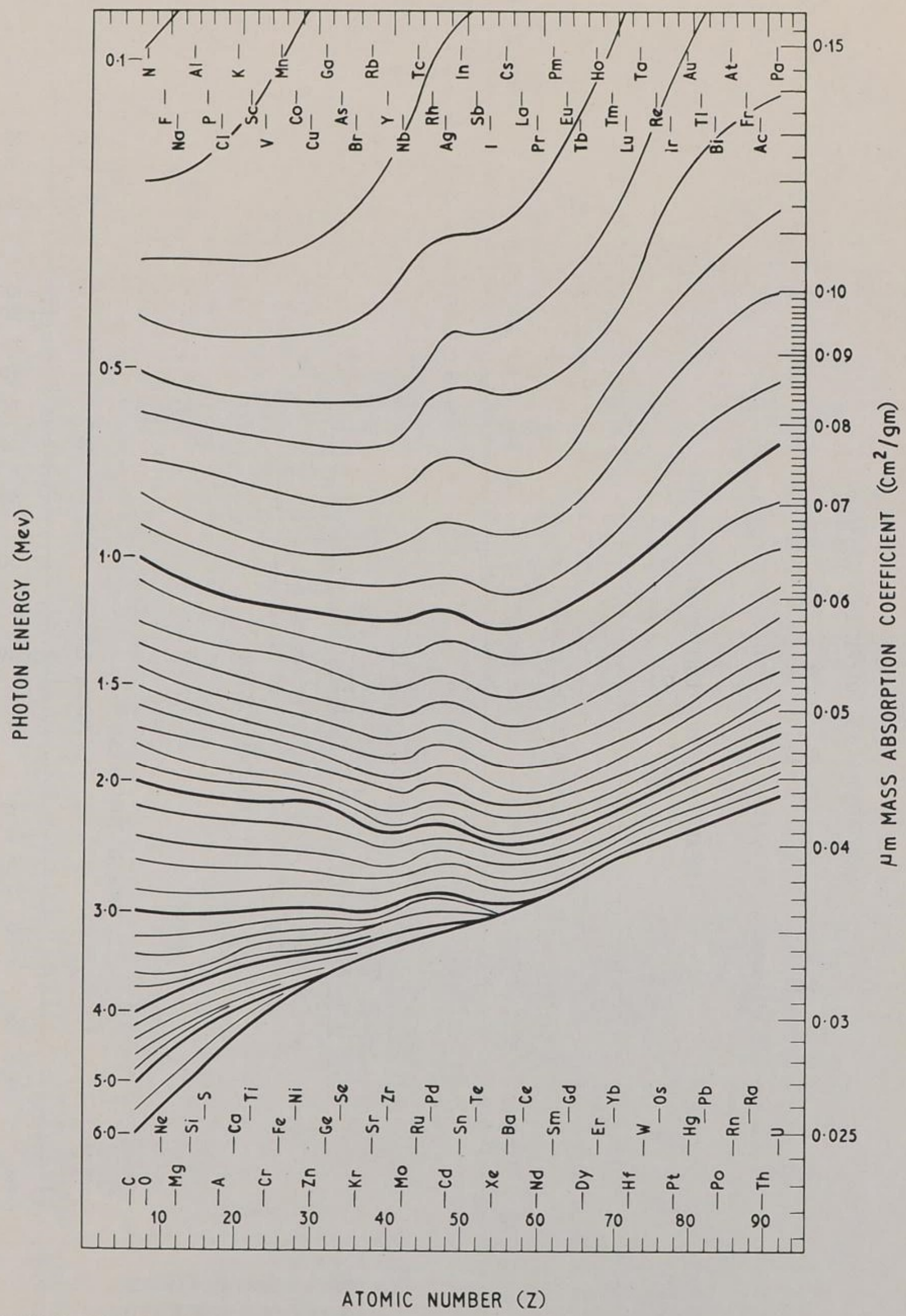

THE NOMOGRAM, FIG. 4, CAN BE USED TO CONVERT μ_m TO THE LINEAR ABSORPTION COEFFICIENT, μ, BY MULTIPLYING BY THE DENSITY OF THE SHIELD MATERIAL, ρ. IF μ IS CONNECTED TO THE SHIELD THICKNESS, x, THE SHIELD ATTENUATION FACTOR FOR A POINT SOURCE WITH UNIT BUILD-UP, e^{-b}, IS OBTAINED ($b = \mu x$). THE APPROXIMATE BUILD-UP FACTOR, B, FOR MOST ELEMENTS, BUT NOT LEAD, UP TO 3 Mev IS $1 + b$ AND FOR LEAD OVER THE SAME RANGE $1 + \frac{1}{2} b$. THE CORRECTED ATTENUATION FACTOR IS $B \times e^{-b}$.

SOURCE STRENGTH (γ/cm²/sec) FOR AN INFINITE PLANE SOURCE IS APPROXIMATELY $\lambda/2 \times Q_V$, WHERE Q_V IS THE SPECIFIC ACTIVITY, γ/cm³, OF THE SOURCE MATERIAL. IF μ IS DETERMINED FOR THE SOURCE γ-RAY, λ CAN BE READ ON THE ADJACENT SCALE.

MASS ABSORPTION COEFFICIENTS OF THE ELEMENTS

(SEE ALSO FIGURE 4, SECTION 5.1.5)

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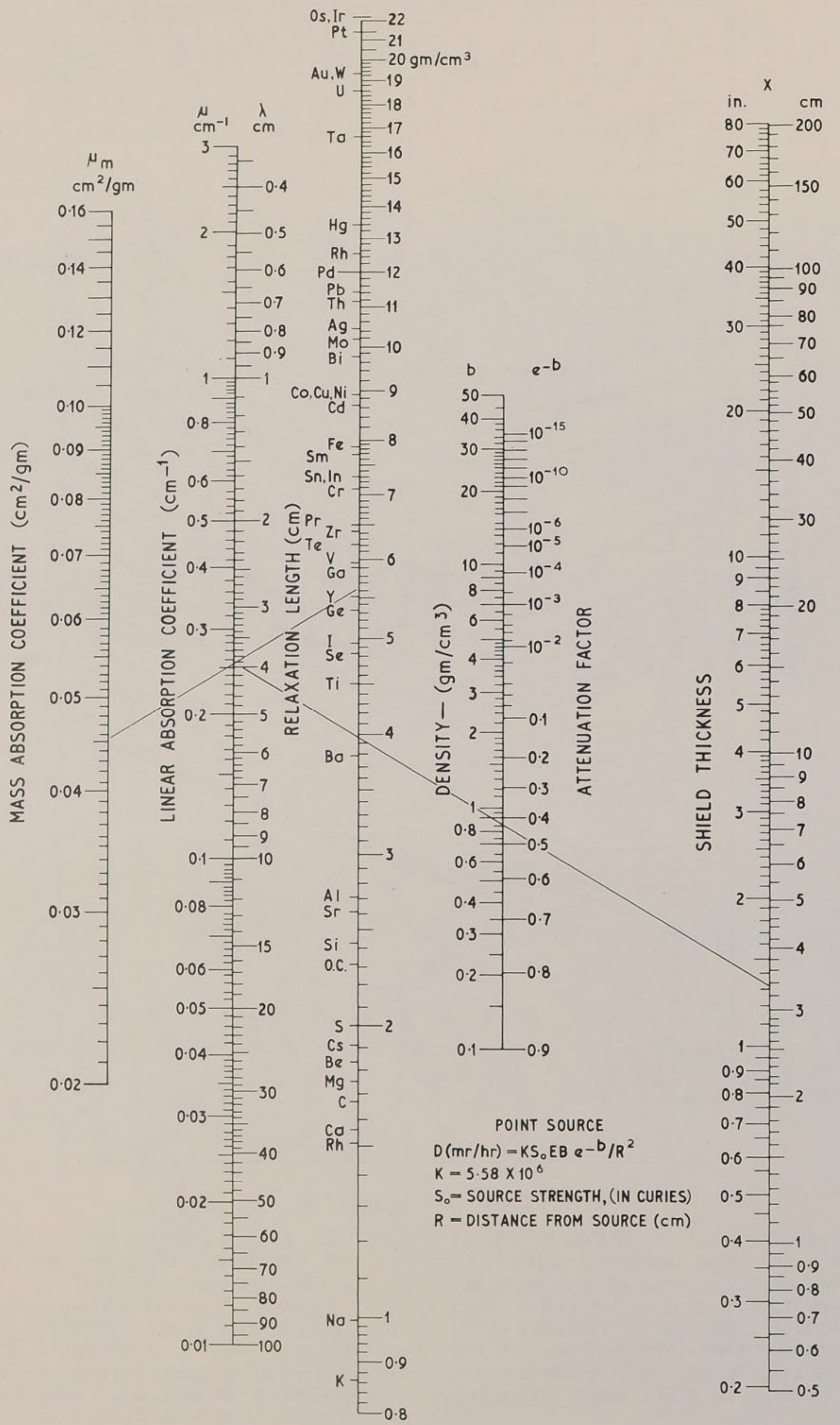

GAMMA-RAY ATTENUATION
(SEE ALSO FIGURE 3, SECTION 5.1.5)

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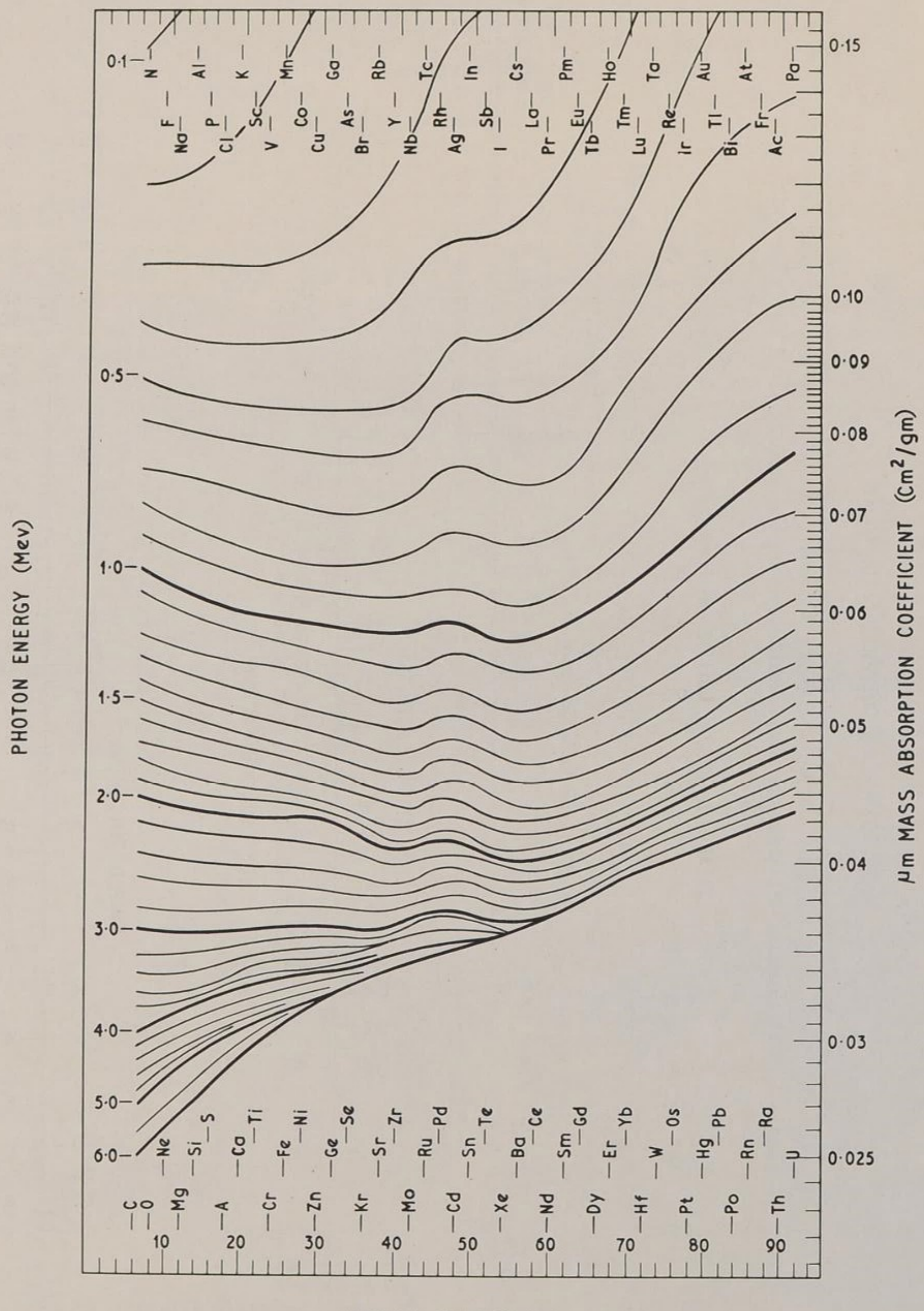

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SOURCE STRENGTH (γ/cm^2/sec) FOR AN INFINITE PLANE SOURCE IS APPROXIMATELY $\lambda/2 \times Q_V$, WHERE Q_V IS THE SPECIFIC ACTIVITY, γ/cm^3, OF THE SOURCE MATERIAL. IF μ IS DETERMINED FOR THE SOURCE γ-RAY, λ CAN BE READ ON THE ADJACENT SCALE.

MASS ABSORPTION COEFFICIENTS OF THE ELEMENTS

(SEE ALSO FIGURE 4, SECTION 5.1.5)

PART VII
CHAPTER 5
SECTION 5.1.5
FIGURE 4

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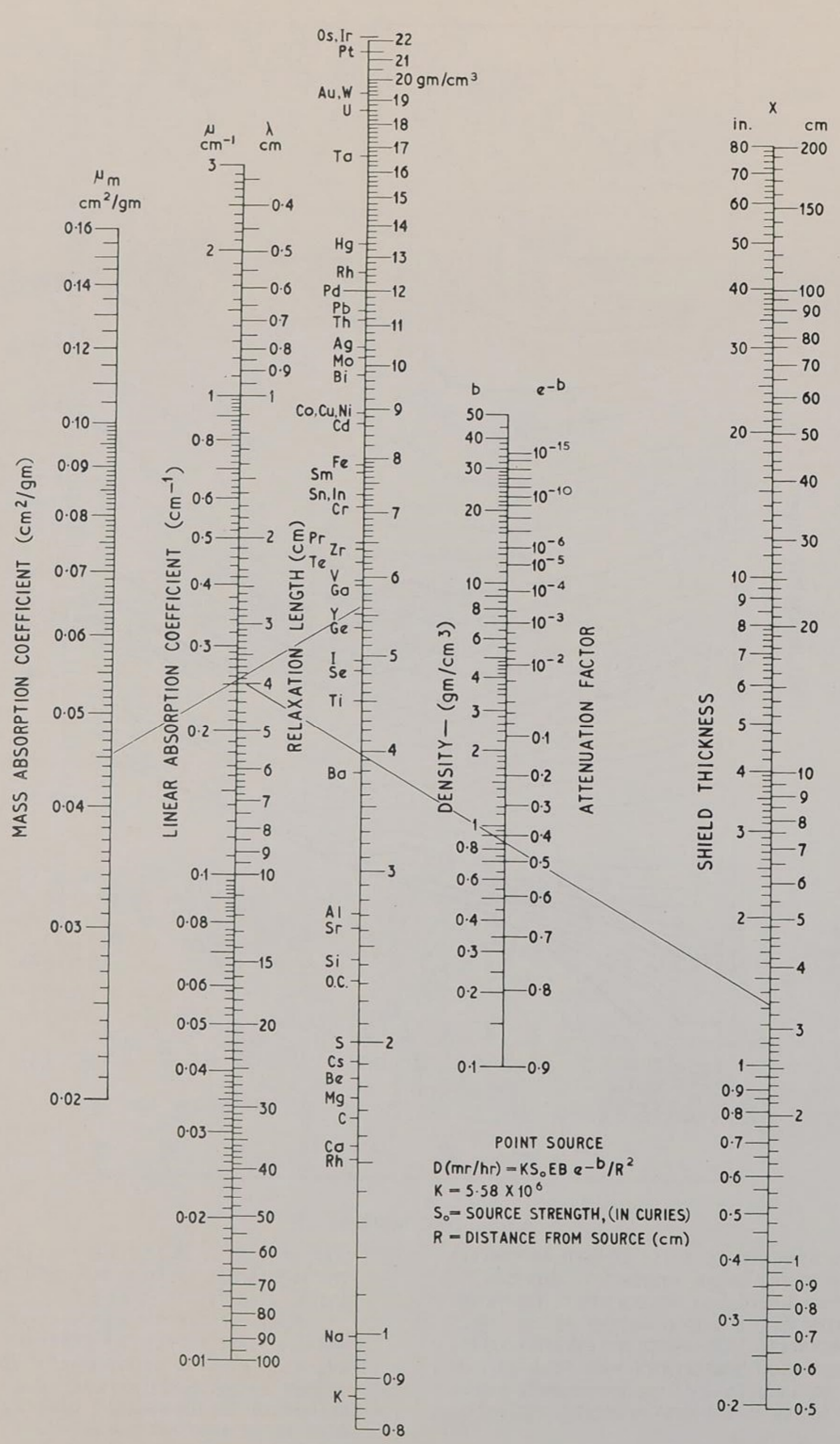

GAMMA–RAY ATTENUATION
(SEE ALSO FIGURE 3, SECTION 5.1.5)

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EXPLANATORY NOTE TO FIGURES 5 AND 6 (GAMMA-RAY SCATTERING FROM THIN SCATTERERS)

Figures 5 and 6 permit rapid estimation of the photon flux reflected from a thin object; this is often required in shield design. A photon flux I_i (γ/cm²/sec) of energy E_i (Mev) per photon, incident upon a scatterer thin with respect to the relaxation length of the incident or scattered photon ($t < \lambda$), will scatter through an angle θ to a receiver R at distance D (cm) with an intensity I_R (γ/cm²/sec/steradian) and energy E_R (Mev) per photon and an intensity given by :-

$$I_R = N_e \sigma_D D^{-2} I_i = K I_i$$

The energy flux, ϕ_ϵ (Mev/cm²/sec/steradian) at R is :-

$$\phi_\epsilon = E_R I_R = PE_i KI_i$$

The scattered photon energy, E_R, is given by the Compton equation:-

$$P = E_R / E_i = \left[1 + \frac{E_i}{0{\cdot}51}(1 - \cos\theta)\right]^{-1}$$

The probability per electron of scattering the incident photon through angle θ is given by the Klein-Nishina equation :-

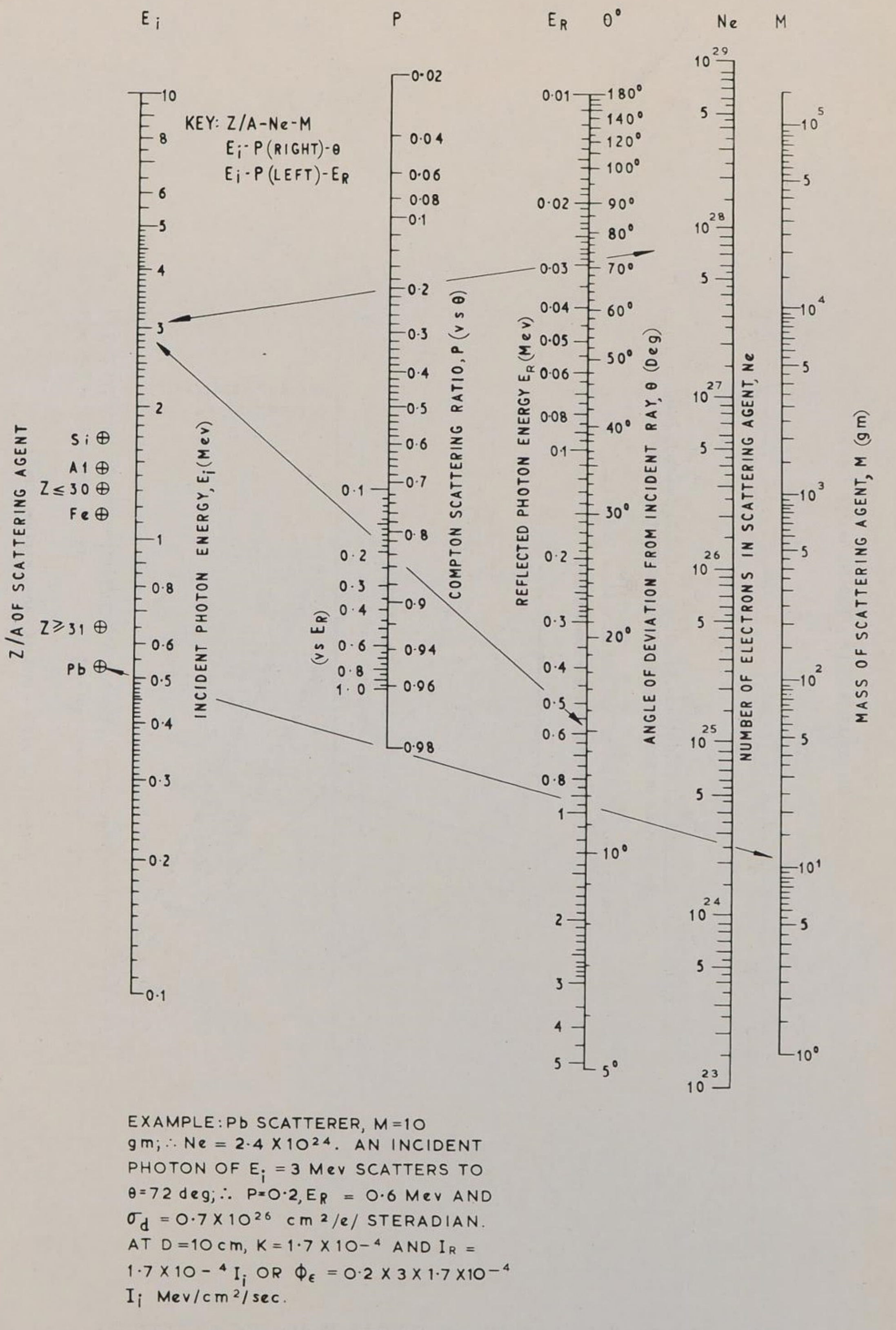
$$\sigma_D = d\sigma/d\Omega = (P - P^2 \sin^2\theta + P^3) r_e^2/2$$

where the classical electron radius $r_e = 2{\cdot}82 \times 10^{-13}$ cm and σ_D is in cm²/steradian per electron. One must multiply by the number of electrons in the scattering medium, $N_e = 6{\cdot}02 \times 10^{23}$ MZ/A, to get the total scattering probability.

Large objects must be subdivided into pieces of such size that I_i and θ can be assumed constant over each region of subdivision. Each region is then considered to be a point scatterer defining a new set of parameters M, D, and θ, and the scattered intensities from all subdivisions are summed.

If small values of M are used, K may go off-scale; in this case N_e can be multiplied by a convenient factor of 10 and K divided by the same factor to obtain the corrected value of K.

The value of K is not particularly sensitive to Z/A. However, the average value Z/A for Z = 2–30 is plotted at $Z \leq 30$ and for Z/A for Z = 31–91 at $Z \geq 31$. This provides for scattering media for which only an approximate composition is known.



EXAMPLE: Pb SCATTERER, M = 10 gm; ∴ Ne = 2·4 X 10²⁴. AN INCIDENT PHOTON OF E_i = 3 Mev SCATTERS TO θ = 72 deg; ∴ P = 0·2, E_R = 0·6 Mev AND σ_d = 0·7 X 10²⁶ cm²/e/ STERADIAN. AT D = 10 cm, K = 1·7 X 10⁻⁴ AND I_R = 1·7 X 10⁻⁴ I_i OR ϕ_ϵ = 0·2 X 3 X 1·7 X 10⁻⁴ I_i Mev/cm²/sec.

GAMMA-RAY SCATTERING FROM THIN SCATTERERS
(SEE ALSO FIGURE 6 SECTION 5.1.5)

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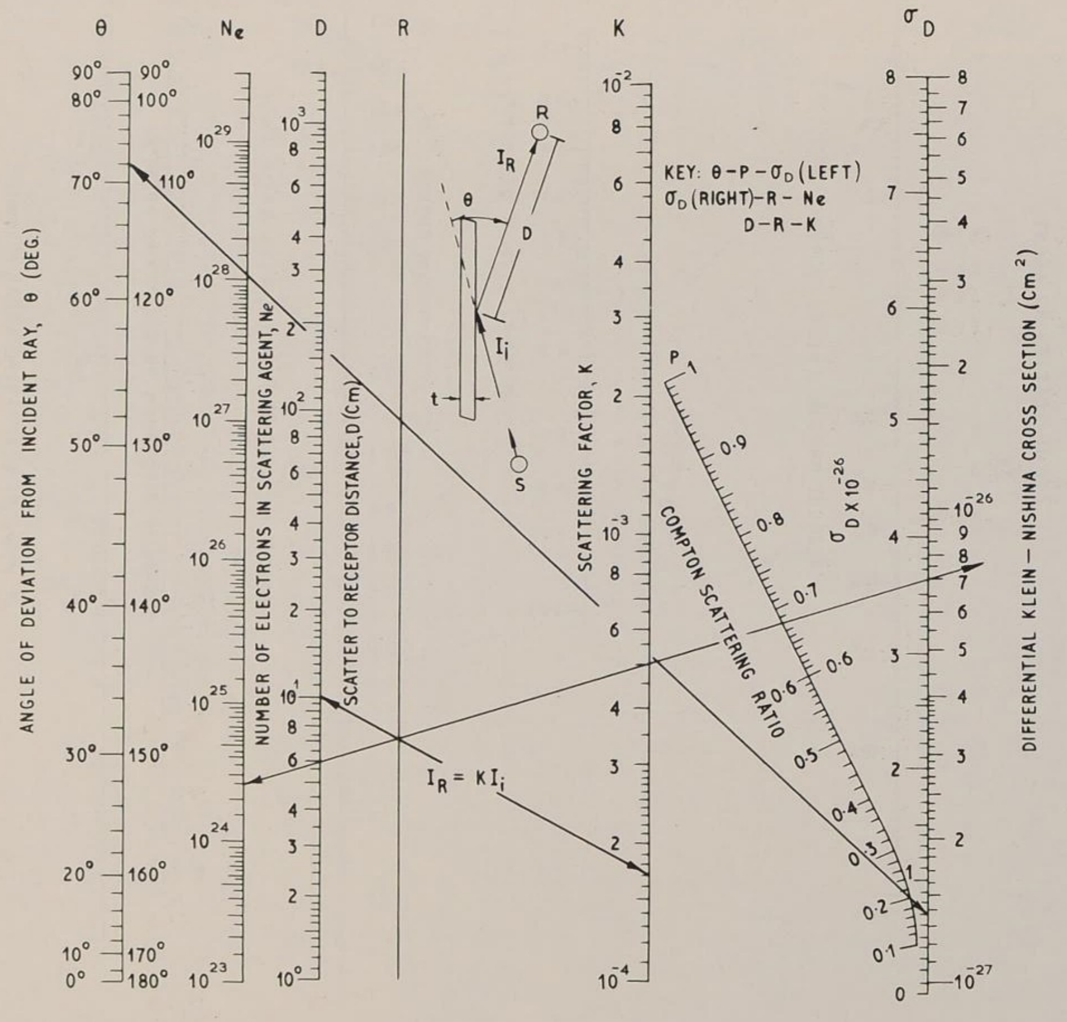
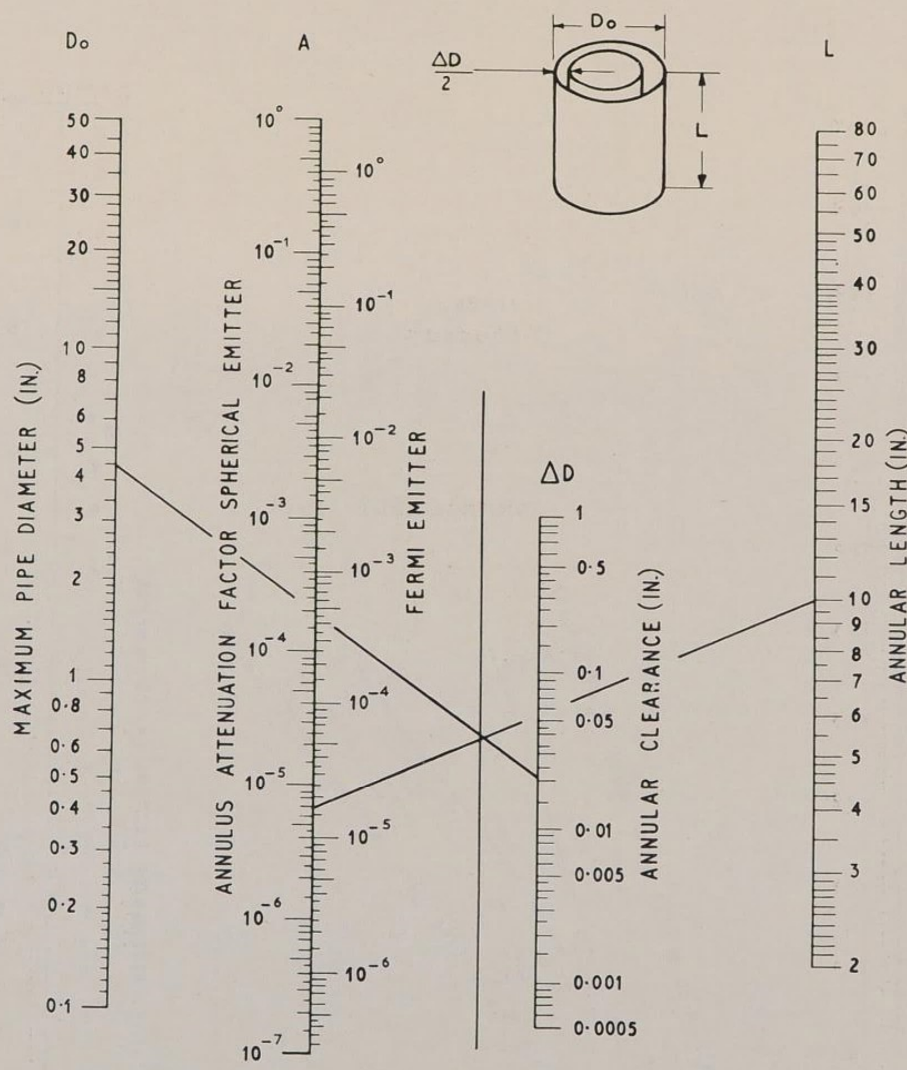


GAMMA-RAY SCATTERING FROM THIN SCATTERERS

(SEE ALSO FIGURE 5, SECTION 5.1.5)



THIS NOMOGRAM PERMITS RAPID AND ACCURATE DETERMINATION OF THE GEOMETRICAL ATTENUATION OF THE GAMMA-RAY FLUX FROM AN EMITTING SURFACE ONTO WHICH THE ANNULUS ABUTS PERPENDICULARLY. SCATTERING EFFECTS ARE NOT ACCOUNTED FOR. THE FORMULA FOR THE ATTENUATION IS :-

$$A = KD_o^{1/2}\,\Delta D^{3/2}\,L^{-2}$$

WHERE K IS $2\cdot8/8\pi$, $5\cdot6/8\pi$ AND $7\cdot2/8\pi$ FOR SPHERICAL, COSINE AND FERMI EMITTERS * RESPECTIVELY. THE OTHER SYMBOLS ARE SHOWN IN THE DIAGRAM ACCOMPANYING THE NOMOGRAM. THE FORMULA IS VALID ONLY IF $L \gg \Delta D$, THE USUAL SITUATION.

EXAMPLE :- ANNULUS WITH $D_o = 4{\cdot}5$ IN. $\Delta D = 0{\cdot}02$ IN. ($\Delta R = 0{\cdot}01$ IN.) AND L = 10 IN ABUTS PERPENDICULARLY ONTO A GAMMA-EMITTING SURFACE. AS SHOWN THE NOMOGRAM GIVES $A = 7{\cdot}0 \times 10^{-6}$ FOR A SPHERICAL EMITTER, $1{\cdot}8 \times 10^{-5}$ FOR A FERMI EMITTER. ATTENUATION FOR A COSINE EMITTER IS TWICE THAT FOR A SPHERICAL OR 14×10^{-6}

* WHEN SOURCE DENSITY INCREASES WITH DEPTH AND THERE IS SELF-ABSORPTION THE RADIATION PASSING THROUGH THE INTERFACE WILL BE ENHANCED IN THE FORWARD DIRECTION. A GOOD APPROXIMATION TO THE DISTRIBUTION IS GIVEN BY THE FERMI FORMULA.

$$N(\theta) = \sim \cos\theta - \sqrt{3}\cos^2\theta$$

GAMMA - RAY STREAMING THROUGH AN ANNULUS

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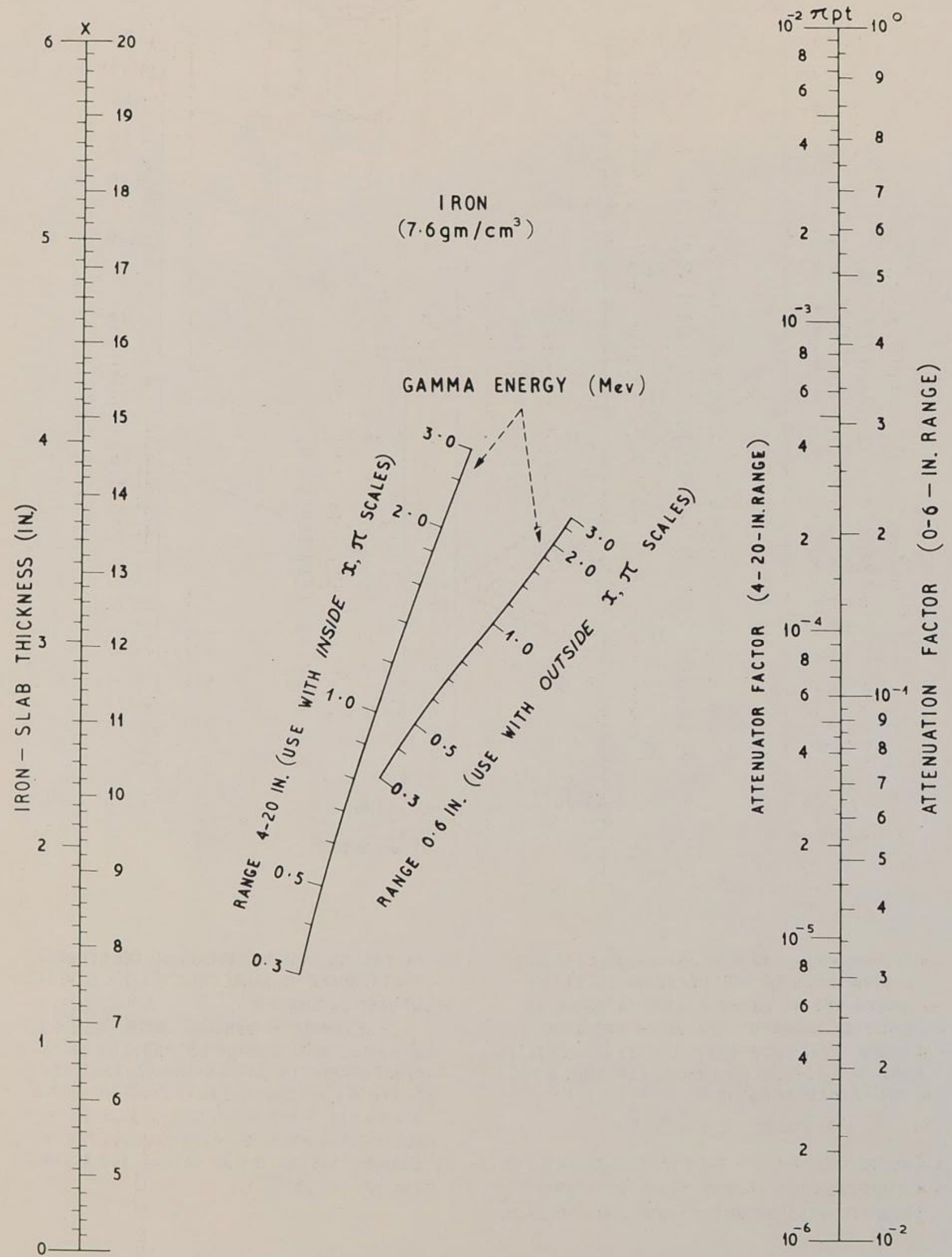

GAMMA ATTENUATION WITH BUILD-UP IN IRON
(FOR NOTE ON USE – SEE FIGURE 9, SECTION 5.1.5)

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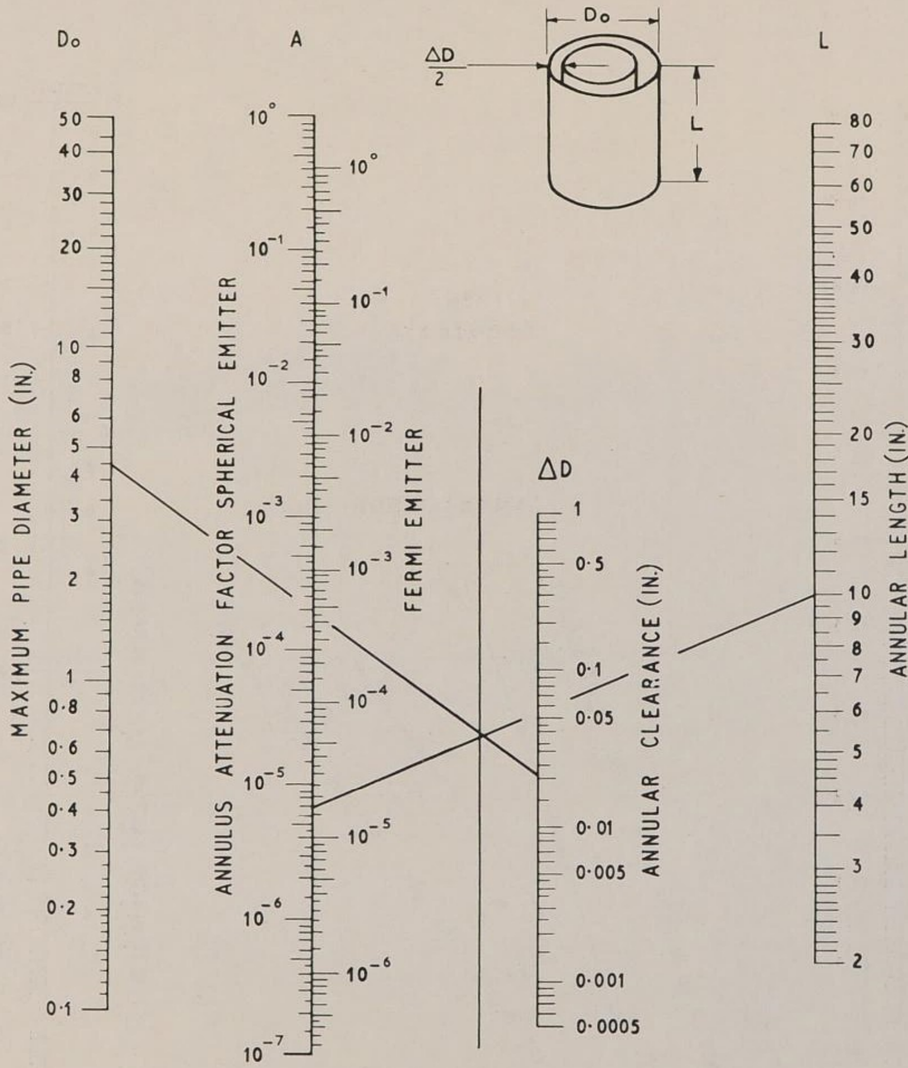


THIS NOMOGRAM PERMITS RAPID AND ACCURATE DETERMINATION OF THE GEOMETRICAL ATTENUATION OF THE GAMMA-RAY FLUX FROM AN EMITTING SURFACE ONTO WHICH THE ANNULUS ABUTS PERPENDICULARLY. SCATTERING EFFECTS ARE NOT ACCOUNTED FOR. THE FORMULA FOR THE ATTENUATION IS :-

$$A = K D_0^{1/2} \Delta D^{3/2} L^{-2}$$

WHERE K IS $2 \cdot 8/8\pi$, $5 \cdot 6/8\pi$ AND $7 \cdot 2/8\pi$ FOR SPHERICAL, COSINE AND FERMI EMITTERS * RESPECTIVELY. THE OTHER SYMBOLS ARE SHOWN IN THE DIAGRAM ACCOMPANYING THE NOMOGRAM. THE FORMULA IS VALID ONLY IF $L \gg \Delta D$, THE USUAL SITUATION.

EXAMPLE :- ANNULUS WITH $D_0 = 4 \cdot 5$ IN. $\Delta D = 0 \cdot 02$ IN. ($\Delta R = 0 \cdot 01$ IN.) AND $L = 10$ IN ABUTS PERPENDICULARLY ONTO A GAMMA-EMITTING SURFACE. AS SHOWN THE NOMOGRAM GIVES $A = 7 \cdot 0 \times 10^{-6}$ FOR A SPHERICAL EMITTER, $1 \cdot 8 \times 10^{-5}$ FOR A FERMI EMITTER. ATTENUATION FOR A COSINE EMITTER IS TWICE THAT FOR A SPHERICAL OR 14×10^{-6}

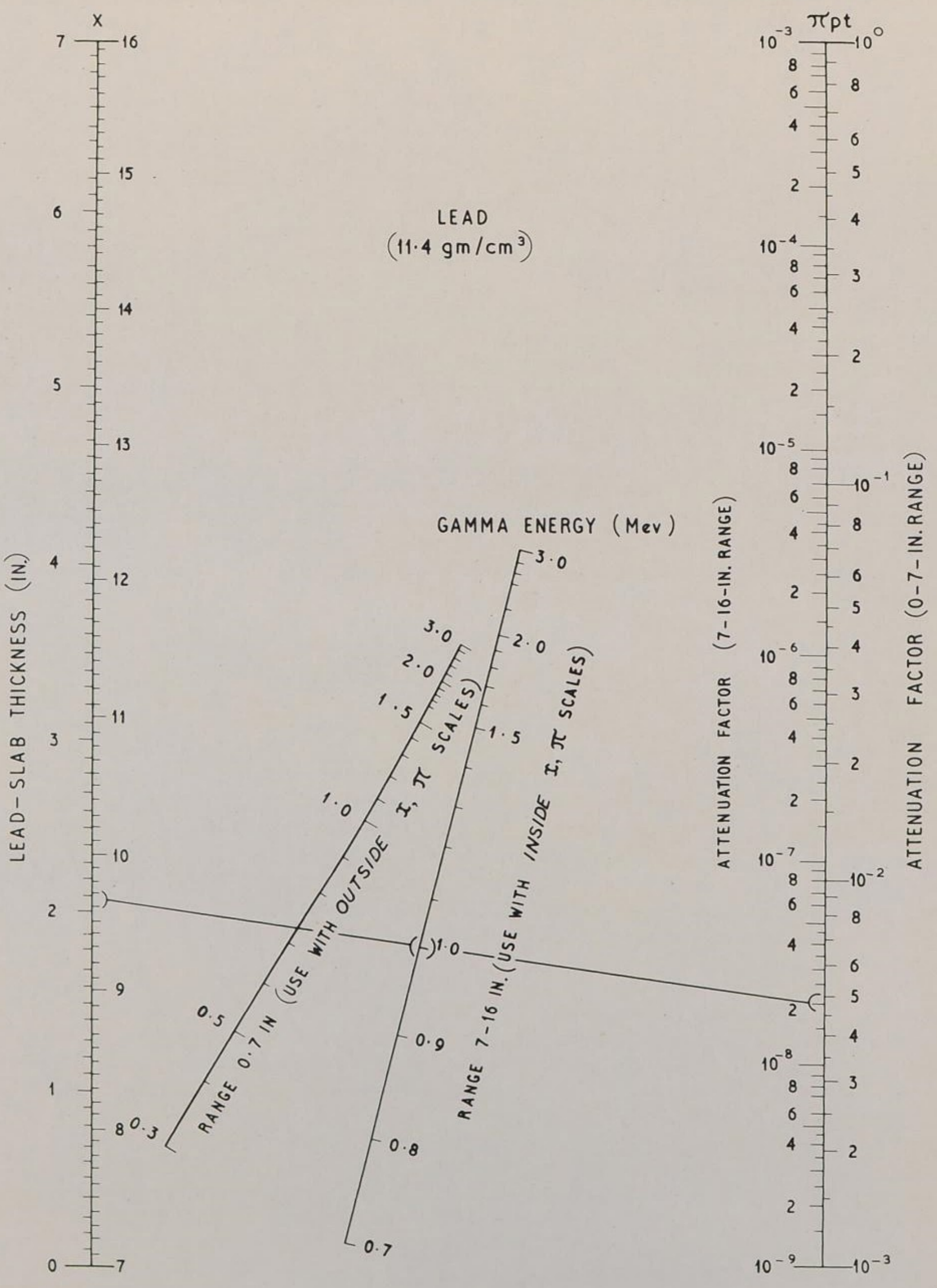
* WHEN SOURCE DENSITY INCREASES WITH DEPTH AND THERE IS SELF-ABSORPTION THE RADIATION PASSING THROUGH THE INTERFACE WILL BE ENHANCED IN THE FORWARD DIRECTION. A GOOD APPROXIMATION TO THE DISTRIBUTION IS GIVEN BY THE FERMI FORMULA.

$$N(\theta) = \sim \cos\theta - \sqrt{3} \cos^2\theta$$

GAMMA - RAY STREAMING THROUGH AN ANNULUS

FIGURES 8 & 9 GIVE ATTENUATION FACTORS FOR LEAD AND IRON SHIELDING SLABS USED WITH POINT SOURCES OF GAMMA RADIATION. THE NOMOGRAMS INCLUDE THE EFFECT OF BUILD-UP—THE SCATTERING OF DEGRADED RADIATION INTO THE BEAM FROM ALL POINTS OF THE ABSORBER. OVER MOST OF THE RANGE, ACCURACY IS 10% OR BETTER. AT EXTREME POSITIONS ACCURACY IS BETTER THAN 25%.

EXAMPLE:- HOW THICK MUST A LEAD SHIELD BE TO REDUCE THE DOSE FROM A POINT SOURCE OF 1.0 – Mev GAMMAS BY A FACTOR OF 2×10^{-8}?
WE DRAW A LINE FROM THE NUMBER 2×10^{-8} AT THE RIGHT THROUGH 1.0 – Mev ON THE PROPER GAMMA – ENERGY SCALE.
READING ON THE APPROPRIATE SIDE OF THE SLAB-THICKNESS SCALE WE FIND THE ANSWER: 9·67 IN.



GAMMA ATTENUATION WITH BUILD-UP IN LEAD

5.1.6 Shielding by some common structures

The shielding data for parallel beams of radiation falling on simple shields are only of limited value in dealing with the protection afforded by actual structures. A few results are available from trials of weapons in the kiloton range and these, together with the results of some theoretical studies, are given here:-

(i) Concrete cubicles

At Operation Hurricane (Reference (1)) a number of concrete cubicles were built and gamma ray attenuation measurements were made by means of film badges placed across each cubicle, all at a height of 6 ft. The concrete had a density of about 133 lb./cu.ft. and the cubicles had sides 12 ft. long and 12 ft. high. The following results were obtained:-

Wall thickness (inches)	No. of badges	Attenuation Factor Average	Range
$6\frac{3}{4}$	4	0.16	0.15 - 0.20
$9\frac{3}{4}$	3	0.096	0.082 - 0.12
12	4	0.064	0.057 - 0.079

Further observations on the penetration of concrete slabs by initial gamma radiation were made at Operations Totem and Buffalo (see also Section 5.1.5 of this chapter). It would appear from the evidence available (Reference (2)) that the gamma radiation from Buffalo Round 1 was substantially harder than that from Totem Round 1. The Buffalo half-thickness was about $4\frac{3}{4}$ inches of concrete (or 51 lb./ft.^{2}) compared with the Totem half-thickness of about $1\frac{3}{4}$-$2\frac{1}{2}$ inches of concrete (or 20-29 lb./ft.^{2}). The American data summarized in Reference (5) are more nearly in accord with the Buffalo results.

(ii) Anderson Shelters

A limited amount of information on these shelters was obtained at Operation Hurricane (Reference (1)). Owing to the irregular shape of this type of shelter, and the impossibility of maintaining a constant soil coverage, the results vary from one shelter to another. On average however, it was found that the attenuation factor in that part of the shelter which was above ground was about 0.03, while for the underground part of the shelter the factor was about 0.02. The penetration of Anderson shelters by initial gamma radiation was also studied at Operation Buffalo (Reference (2)) but the results showed considerable variation. A mean attenuation factor of about 0.05 was obtained.

(iii) Trenches

The protection afforded by trenches has been studied by A.O.R.G. (Reference (3)), and information obtained from tests with slit trenches and circular holes at Operation Totem, has been reported (Reference (4)).

The protective value of a trench depends on several factors, such as depth, orientation, nature of soil, amount and type of cover, angle of elevation to the burst, and the position at which the dose is measured. Some average figures for trenches 6' x 2' x 4'6" deep have been taken from the A.O.R.G. Report (Reference (3)) and are shown in Figure 1. Some values for gamma attenuation factors for circular pits at Operation Totem (Reference (4)) are given in Table 1. These pits were 6 ft. deep and 4 ft. in diameter, and those designated 'closed' were completely covered by an 18 inch thick layer of sandbags. The dose measurements were made with film badges mounted at the

stated heights on the centre line of each hole.

TABLE 1

Gamma Attenuation Factors for Circular Pits at Operation Totem

Depth below surface (inches)	Distance from Ground Zero and Exterior Dose							
	1710 ft. (11000r)		2720 ft. (950r)		3760 ft. (110r)		6010 ft. (4.7r)	
	Open	Closed	Open	Closed	Open	Closed	Open	Closed
0	1.0	96	1.0	63	1.0	78	1.0	36
6	2.1	100	3.7	56	2.8	55	3.4	39
12	3.8	105	7.3	53	5.2	52	6.5	47
24	12	120	16	79	13	100	15	94
36	21	150	29	155	24	165	24	105
48	38	190	45	250	39	240	34	120
60	58	310	63	320	52	330	48	140
72	92	610	86	380	61	380	64	170

Information on initial gamma attenuation factors, from an American source (Reference (5)), is listed in Table 2.

TABLE 2

Attenuation Factors for Initial Gamma Radiation

Geometry	Attenuation Factor		
Foxholes[a]	0.05	-	0.10
Underground - 3 ft.	.04	-	.05
Frame House			.9
Basement	.05	-	.5
Multistory building			
Upper			.9
Lower	.3	-	.6
Blockhouse walls			
9 inches			.1
12 inches	.05	-	.09
24 inches	.01	-	.03
Shelter, partly above ground level			
with earth cover - 2 ft.	.02	-	.04
with earth cover - 3 ft.	.01	-	.02
Tanks: M-24, M-41; Tank Recov. Veh. M-51, M-74	.1	-	.2
Tanks: M-26, M-47, M-48, T-43E1: Eng. Armd. Vehicles T-39E2	.05	-	.15
$\frac{1}{4}$ ton Truck			1.0
$\frac{3}{4}$ ton Truck			1.0
$2\frac{1}{2}$ ton Truck			1.0
Armd. Inf. Veh. M-59, M-75 and SP Twin 40 mm Gun M-42	.2	-	.5
SP 105 mm Howitzer M37	.4	-	.6
Multiple Cal. .50 m.g. Motor Carriage M-16	.8	-	1.0
LVT (Landing Vehicle Tracked)	.5	-	.9
Battleships and Large Carriers[b]			
15% of Crew			1.0
25% of Crew			.2
10% of Crew			.05
50% of Crew	.0005	-	.005
Cruisers and Carriers[b]			
10% of Crew			1.0
20% of Crew			.5
30% of Crew	.1	-	.3
40% of Crew	.005	-	.1
Destroyers, Transports and Escort Carriers[b]			
10% of Crew			1.0
20% of Crew			.7
30% of Crew			.4
40% of Crew	.1	-	.4

a No line-of-sight radiation received
b Crew at General Quarters

References

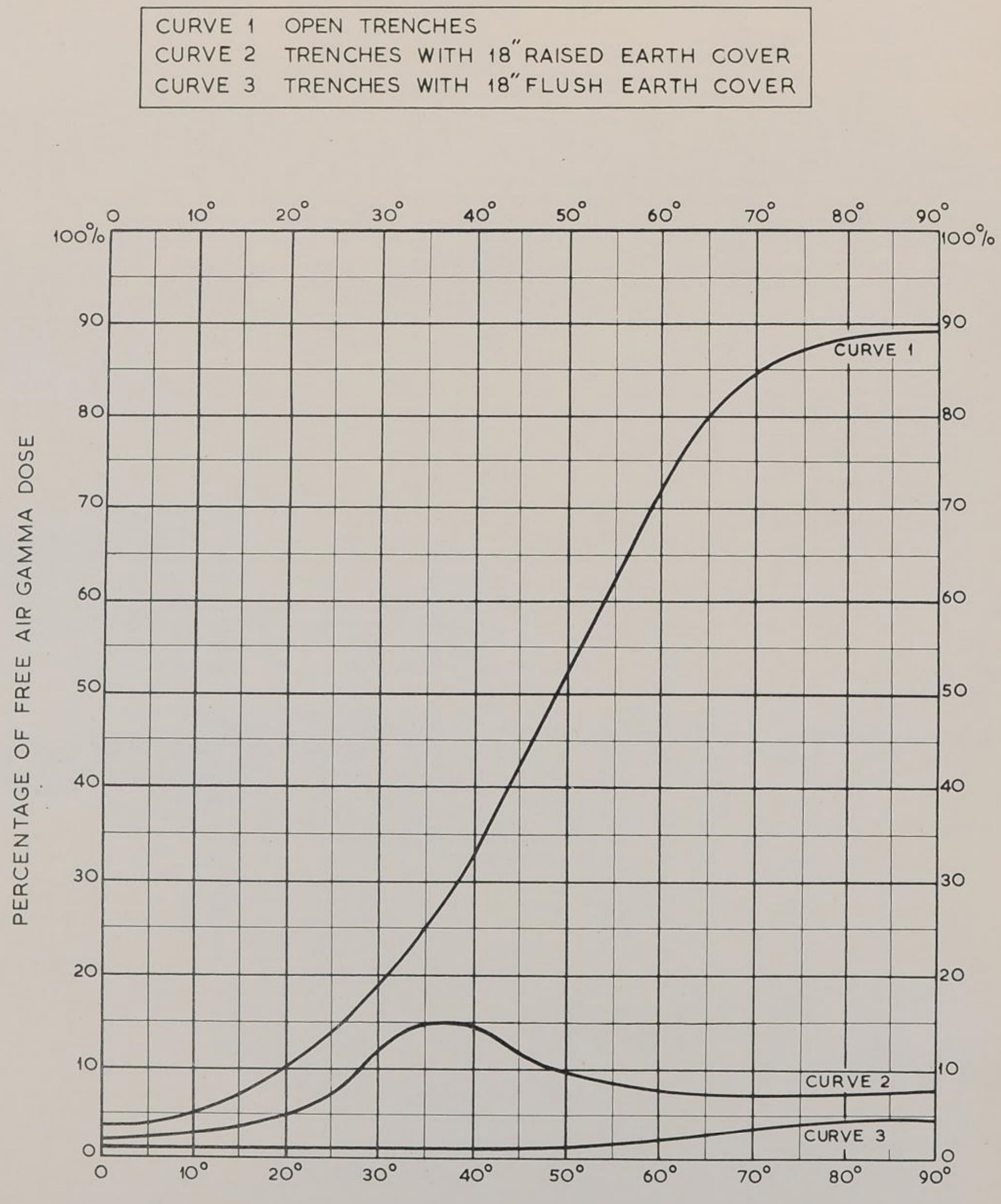
(1) A.W.R.E. Report No. T20/54

(2) A.W.R.E. Report No. T42/57

(3) Army Operational Research Group, Report No. 12/55

(4) A.W.R.E. Report No. T6/56

(5) Capabilities of Atomic Weapons. A.F.S.W.P. TM23-200(1957)
(Confidential/Discreet)



SHIELDING VALUES FOR TRENCHES
AGAINST GAMMA RADIATION

5.2 Neutrons

5.2.1 Basic principles

Essentially all the neutrons accompanying a nuclear explosion are released either in the fission or fusion process. All of the neutrons from the latter source and over 99% of the fission neutrons are produced almost immediately, probably within less than a millionth of a second of the initiation of the explosion. These are referred to as the 'prompt' neutrons.

In addition, somewhat less than 1% of the fission neutrons, called the 'delayed' neutrons, are emitted subsequently. Since the majority of these 'delayed' neutrons are emitted within the first minute, however, they constitute part of the initial nuclear radiation. Some neutrons are also produced by the action of gamma rays of high energy on the nuclear bomb materials, but these make a very minor contribution and so can be ignored.

Neutrons bear no charge and so do not directly ionise the medium through which they are moving. Their mass is comparable to that of the lighter elements, and they may undergo strong interactions with nuclei. Because of these two properties, neutrons may cause ionisation indirectly (a) by elastic collisions, and (b) by capture by nuclei.

(a) Elastic collisions - In an elastic collision the neutron and the nucleus with which it collides may be considered to behave as rigid spheres. If the neutron is moving so fast compared with thermal velocities that the nucleus with which it collides may be treated as being at rest, the energy of this nucleus after the collision will be between 0 and E_{max}, where:

$$E_{max} = \frac{4A}{(A + 1)^2} E \qquad (5.2.1)$$

E = The energy of the neutron before collision

A = The atomic weight of the nucleus.

For light elements the scattering is usually isotropic, and in this case the average energy of the nucleus will be $\frac{1}{2} E_{max}$. Thus, in an elastic collision a neutron with kinetic energy greater than about 1 Kev can impart enough energy to a light nucleus to enable that nucleus to ionise the material through which it moves. The density of ionisation caused by such a nucleus is very great and therefore its range will be very much shorter than that of an electron of the same energy (approximately $\frac{1}{100}$ for the H nucleus).

(b) Neutron capture - Any interaction between neutrons and nuclei other than elastic scattering is considered to proceed through the formation of a 'compound nucleus' made up of the incident neutron and the nucleus it has struck. This compound nucleus is invariably formed in an excited state and it may lose this excitation energy in a variety of ways, with corresponding end products.

(i) Inelastic scattering - The compound nucleus emits a neutron of energy less than that of the incident neutron, and a gamma-ray. This process can only occur if the energy of the incident neutron exceeds that of the first gamma emitting state of the target nucleus. This threshold energy effect is also shown by the capture processes involving charged particle emission. The process of inelastic scattering is denoted by $(n, n\gamma)$, where the symbol before the comma denotes the ingoing particle, and the symbols after the comma represent the outgoing particles.

(ii) Radiative capture (n,γ) - In this case a gamma-ray only is emitted after the neutron has been captured. This is the most common reaction between nuclei and thermal neutrons. Highly energetic gamma rays can be produced. The resulting nucleus, of increased atomic weight, may be unstable.

(iii) Charged particle emission - (n, q) - The particle emitted is usually either a proton (n, p) or an alpha particle (n,α); more rarely other light nuclei may be emitted. There are two important cases where charged particle emission may follow the absorption of a thermal neutron, namely N^{14} (n, p) and B^{10} (n,α). These charged particles will have a short range and be densely ionising. It should be noted that the nucleus remaining after (n,γ) or (n, q) may be radioactive.

The probability of occurrence and relative importance of these processes vary considerably with the energy of the neutrons and the composition of the material through which they are moving. In dealing with the effect of neutrons from a nuclear weapon on any target it is therefore necessary to know something of the neutron energy spectrum, that is the distribution of energy values among the neutrons, as well as of the composition of the target. Since the prompt neutron energies are fairly well known, it should be possible, in principle, to calculate the energy spectrum of the neutrons after penetrating the bomb materials. However, since these materials are not completely dispersed when the neutrons are emitted, the neutron spectrum depends on the detailed geometry of the bomb components at an extremely complex stage of the explosion. Variations in bomb design may therefore give rise to wide variations in the energy distribution and intensity of the neutron flux. Because of this, a theoretical solution is virtually impossible and one must resort to experiments.

It is, however, very difficult to measure the neutron spectrum from a nuclear explosion at distances of interest. The method at present adopted is to estimate the number of neutrons with energies above certain values by measuring the activity induced in suitably chosen targets which can be activated only by neutrons having energies above these values. The interpretation of the results obtained may give rise to difficulties.

Elastic and inelastic scattering eventually reduce the energy of all neutrone that are not absorbed to a level where they are in thermal equilibrium with the surrounding medium (thermal neutrons); at normal temperatures this energy is about 0.025 ev. At energies of this order the cross section for the (n,γ) process in many elements is large, and when the product nucleus is radioactive and has a suitable half-life (of the order of a few hours), targets of such elements provide a convenient method of estimating the number of 'thermalised' and 'nearly thermalised' neutrons reaching the target.

A detailed account of the mechanisms and problems of neutron shielding is given in Chapters 3 and 4 of Reference (1).

References

(1) "Radiation Shielding". B.T. Price, C.C. Horton, and K.T. Spinney. (Pergamon Press, 1957)

5.2.2 Yield and Energy Spectrum

The neutron flux in various energy bands, and the neutron dose, have been measured over a range of distances from nuclear weapons at a number of trials. Up to the present, British measurements of the neutron spectrum have been limited to assessing the numbers of neutrons reaching the target in two energy groups which are referred to as fast and slow neutrons. The number of fast neutrons is deduced from the activation of S^{32} by the (n,p) reaction which is considered to have a threshold at 2.5 Mev and yields P^{32}, a beta emitter with a half-life of 14.3 days. The number of slow neutrons, i.e. neutrons with energy below about 0.2 ev, is deduced from the activity induced in target materials in which an (n,γ) reaction produces a radioactive nucleus.

In order to estimate the number of neutrons with energies between 0.2 ev and 2.5 Mev the Americans have used detectors of U^{238} (which has a threshold for fission with neutrons at 1.5 Mev), Np^{237}, (fission threshold 0.7 Mev), and Pu^{239} in a boron shield, (fission threshold 100 ev). The results show that at distances greater than 1,500 feet from the explosion the proportion of neutrons in each of the energy bands is approximately the same for all distances and for all weapons, although the total flux decreases rapidly with increasing distance. This is illustrated in Figure 1 which is derived from data given for a 20 KT weapon in References (1) and (2). It gives the number of neutrons/cm^2 in each energy group reaching the groun as a function of distance from the explosion.

However, the external neutron yield per kiloton varies considerably with the design of the weapon. The extent of this variation in American weapons is shown in Figures 8 and 9, Chapter 3, Section 3.1, which show the upper and lower limits of neutron dose per kiloton as a function of distance and are taken from Reference (3). A similar spread is shown in the values obtained on British tests of weapons in the kiloton range (Reference (4)). According to Reference (5) the values given in Figure 1 apply to a low neutron yield weapon.

References

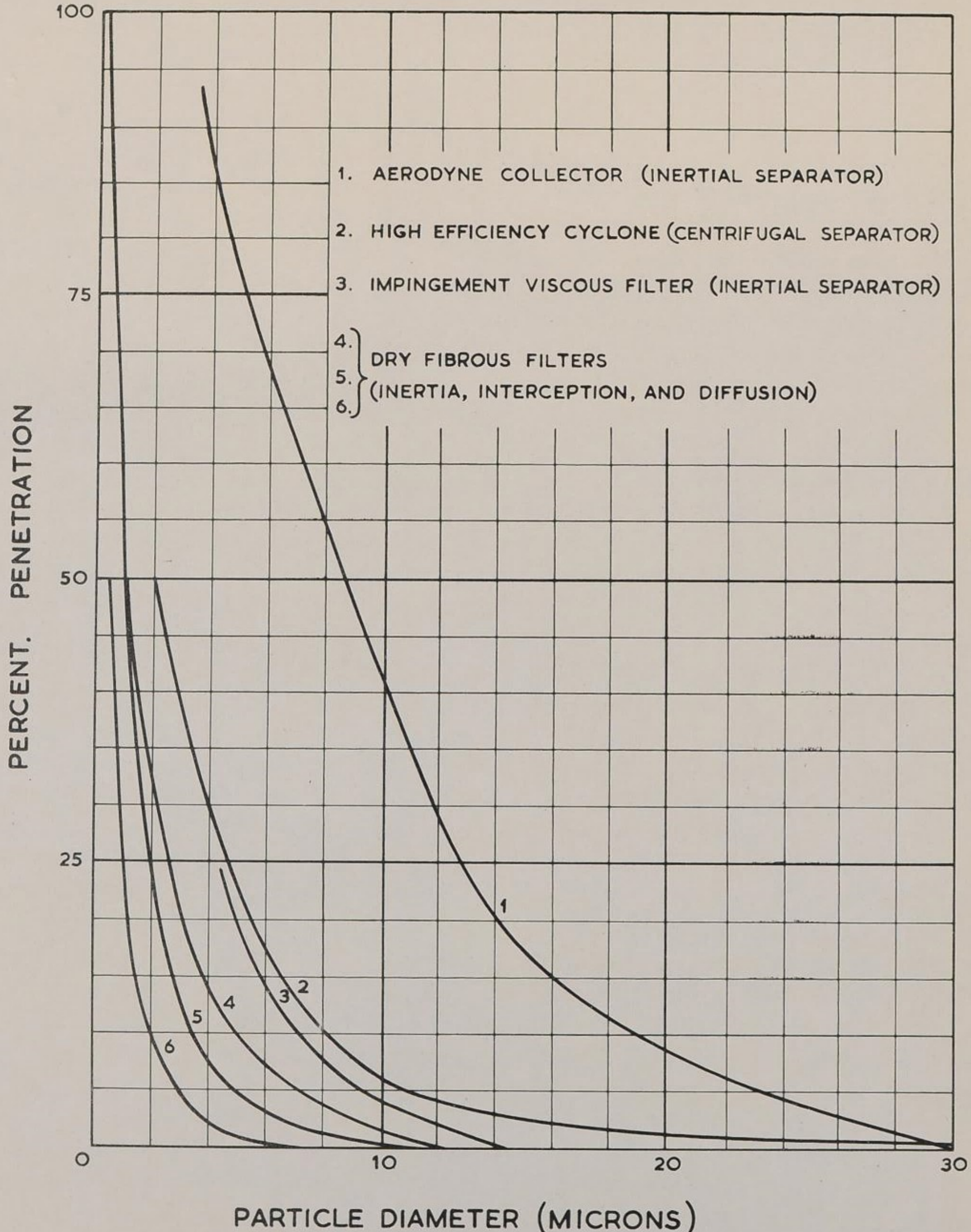
(1) The Effects of Atomic Weapons, page 243, U.S.A.E.C., 1950.

(2) The Effects of Nuclear Weapons, page 385, U.S.A.E.C., 1957.

(3) Capabilities of Atomic Weapons, A.F.S.W.P. TM.23-200 (1955) (Confidential/Discreet)

(4) A.W.R.E. Report No. T59/57.

(5) A.W.R.E. Report No. E5/54.



FILTER EFFICIENCIES

7.7.3. Filters

The problem of cleaning contaminated air supplies to buildings etc. may be overcome by the installation of an adequate filtration system to the air intake. Factors to be considered in designing a filtration system include the size-distribution of the cloud to be filtered, the air requirements, the available space, the pressure-drop limits, and the degree of filtration considered to be adequate. The latter includes an estimate, at present somewhat uncertain, of the relationship between particle size and activity.

Although a large number of filtration systems are available, the basic principles underlying their operation are few, and comprise centrifugal and inertial forces, interception, diffusion and electrostatic forces. A detailed discussion of these principles is beyond the scope of this manual, but their application is illustrated by the curves in Figure 1, which give performance data for some typical filters.

These curves show the penetration/particle size characteristics of the various filters. As a general routine however, it is convenient to compare filters by reference to some standard test. In the case of fibrous filters, the methylene blue test described in British Standard Specification 2831:1957 is a convenient method. Essentially it consists of determining the mass penetration of a methylene blue dye cloud by comparing the density of stains corresponding to known volumes of the filtered and unfiltered cloud. The mass median diameter of particles in the methylene blue cloud is about 0.5 microns, and constitutes a severe test for filters.

The problem of filtering particulate matter arising from nuclear explosions may be considered in terms of the two hazards (cloud contamination and surface contamination) discussed in Sections 7.6.1 and 7.6.2 respectively.

Aircraft will require a filter of high efficiency against rather small particles, since this filter may have to deal with the cloud of condensed-fission products alone. The curves in Figure 1 indicate that a dry fibrous filter will be needed, the actual details being subject to practical design considerations. As an illustration, a comparison between the methylene blue penetration and the estimated fission product cloud penetration for three types of fibrous filter are given below.

Filter 1 - Methylene blue penetration 50%

Mass penetration of fission product cloud, 6.0%

Particle diameter (microns),	0.5,	1.0,	2.0,	3.0
Percent penetration	50.0,	25.0,	10.0,	4.0

Filter 2 - Methylene blue penetration 25%

Mass penetration of fission product cloud 2.0%

Particle diameter (microns)	0.5,	1.0,	2.0
Percent penetration	25.0,	10.0,	1.0

Filter 3 - Methylene blue penetration 0.05%

Mass penetration of fission product cloud, 0.001%

Particle diameter (microns)	0.5,	1.0
Percent penetration	0.05,	0.001

Filters for dealing with fallout will probably be satisfactory if they prevent the penetration of particles greater than about 10 microns diameter, since the evidence available indicates that the greater part of the material will consist of particles larger than 10 microns. It is not however, certain whether the activity will be reduced in proportion to the mass filtered. Examination of Figure 1 shows that practically all the filters would remove a substantial part of the fallout, and that there is considerable scope for the design of systems capable of dealing with this hazard. The concentration of activity by the filter may lead to a radiation hazard, and the siting of the filter and the provision of protection for plant room operators will have to be considered.

In a study of filters suitable for use against fallout, Thomas (Reference (1)), concludes that impingement type filters (e.g. oil-coated glass fibre, oiled metal gauze, etc.) could not be relied upon to provide adequate filtration, but that the overall performance of the fabric bag and the thin dry fibrous air conditioning types of filter should be satisfactory, provided the face velocity is limited to a maximum of 70 feet/minute. It is suggested by Thomas that a maximum methylene blue penetration of 90% and a maximum face velocity of 70 feet/minute be specified for fibrous filters against fallout.

For further general information on the subject of particulate clouds and dust, including their filtration, the reader is referred to the recent book by Green and Lane, Reference (2).

References

(1) Thomas, D. H. "Filters for Fallout", Porton Technical Paper No. 595, April, 1957. (Confidential)

(2) Green, H. L. and Lane, W. R. - "Particulate Clouds, Dusts, Smokes and Mists", (Spon, 1957)

7.7.2. Protective clothing

Radioactive dust may be encountered during a period of fallout, or later, in association with contaminated ground. The radiation from the airborne dust will always be small, and in the latter instance negligible in comparison with that from the ground. Wearable clothing has no effect on the gamma intensity, although it may somewhat reduce the beta intensity. Although clothing will therefore give little direct protection, it is of value in acting as a barrier to dust contamination which can be removed after the period of exposure and destroyed or decontaminated. By this means the need to decontaminate exposed parts of the body and the ordinary clothing can be avoided.

Requirements

These may be considered under the following headings:-

(1) Resistance to penetration by dust

(2) Low dust retention

(3) Ease of decontamination

(4) Good comfort and wearability

(5) Low cost and avoidance of use of scarce materials

(6) Rain or showerproofness

(7) Durability.

The individual requirements for protective clothing are inter-related, and the best practical garments are those which afford the best compromise. The greatest resistance to penetration will obviously be afforded by impermeable materials whose smooth surfaces also retain very little dust, and are usually (but not necessarily) relatively easy to decontaminate; such materials may cause severe thermal stress and be wearable only for short periods, particularly when heavy work is being performed. Permeable fabrics, if made smooth and fairly close-woven, can give good protection, and are much cooler, but would probably be inadequate against wet fallout.

Materials

Information regarding the suitability of different materials for use in protective garmetnts, is scanty. In the impermeable class, P.V.C. and particularly rubber, are difficult to decontaminate; polythene and polystryrene are the best of the commonly available materials. Permeable fabrics vary considerably, both in the degree of take-up and ease of decontamination. Terylene and nylon fabrics are better in both respects than those made from natural fibres. Wool retains more dust than cotton, but is more easily decontaminated. Improved methods of decontamination may be more effective for one material than for another, and thus may change the order of preference. However, it is most likely that other factors than dust take-up and ease of decontamination will continue to determine the materials used.

Three distinct conditions can be envisaged which would have a bearing on the protective clothing requirement:-

(1) Exposure to wet fallout

(2) Exposure to dry fallout

(3) Heavy or moderate work under dust-raising conditions in a contaminated area.

(1) and (2) may occur during the evacuation of an area after a nuclear explosion. In view of the likely incidence of rain, clothing for this purpose could be impermeable, but there would be no need for durability, and a light plastic garment would be adequate. Decontamination would probably not be required, in which case P.V.C. would suffice. (3) would normally be after fallout had occurred, and the hazard would therefore be less under wet conditions, which would keep the dust settled. Fairly heavy duty permeable fabric, showerproofed would provide the best compromise between resistance to penetration and comfort. The clothing designed for use at British atomic weapon tests, was made of this type of material.

Design of Clothing

The clothing must cover the whole body. Essentially, this calls for a one or two-piece suit with dust closure at the wrists and ankles, and a hood covering the head. When necessary, the face will be covered with a full-face respirator or half-mask and eye-shield. Difficulty was experienced in decontaminating the rubber boots used at 'Hurricane' and other Operations, and the problem of footwear and over-boots is still under investigation.

An account of a clothing trial made during Operation 'Buffalo' is given in Reference (1), Various types of military and protective clothing were tested in a fallout area, and the degree of protection afforded and the extent to which the clothing became contaminated were investigated. Under the conditions of test all the types of clothing tested gave adequate protection. provided the whole body was covered. Ease of decontamination was dependent on the nature and weight of the fabric, and in this respect the A.W.R.E. Combination suit and khaki drill were superior to the gaberdine Combat suit and serge Battle Dress.

Respirators

Respirators are not radiologically necessary for at least the first month after fallout. The question of the biological necessity for wearing respirators in old fallout fields is still under investigation. The wearing of respirators depends on an accurate assessment of the prevailing inhalation and ingestion hazard in relation to the tolerance dose. Complete protection is given by any of the civilian or Servicx type respirators, as well as by the approved commercial dust respirators.

Many respirators have electrically-charged resin-impregnated particulate filters which are adversely affected by large doses of ionising radiation. Attention must be paid to this point in deciding the life of a filter, and also to a possible radiation hazard arising from the concentration of radioactive dust in the filter. In general, it is unlikely that the amount of radioactive dust deposited on the filter during the time the wearer of the respirator receives a tolerance dose from external radiation will have a significant effect on filtering efficiency.

References

(1) A.W.R.E. Report No. T22/57 - Operation 'Buffalo' Decontamination Group Report Parts 1-4 (Confidential)

7.7. Protective Measures

7.7.1. Introduction

Protection against the residual nuclear radiation from fallout presents a number of difficult and involved problems. This is so, not only because the radiations are invisible and require special instruments for their detection and measurement, but also because of the widespread and persistent character of the fallout. In the event of a surface burst of a high yield nuclear weapon for example, the area contaminated by the fallout could be expected to extend well beyond that in which casualties result from blast, thermal radiation and the initial nuclear radiation. Further, whereas the other effects of a nuclear explosion are over in a few seconds, the residual radiation persists for a considerable time.

The general protective measures which can be taken against fallout are as follows:-

(a) Remain in the contaminated area, but take all possible shelter from the radiation from fallout. Reference to Chapter 6 will show that considerable attenuation of gamma rays may be obtained by buildings and especially by earth-covered shelters.

(b) Removal of the population from a contaminated area to a clean or less contaminated one. This may result in greater exposure than by taking shelter, through having to travel without much protection through contaminated areas. At locations relatively near to ground zero, it may be necessary to wait several days before it is possible to come out of shelter without resking a radiation dose of sufficient magnitude to cause severe injury. The more distant a point in the path of the fallout is from the explosion, in the same general direction, the lower will be the initial radiation level, and the shorter will be the duration of the passive protection phase. However, in any area where the contamination is at all serious it will probably be necessary to spend the first day or two after the explosion sheltered from the residual gamma radiation. During the early stages, the activity of the fission products in the fallout is very high, but by the end of 49 hours, or roughly two days, it will have decreased to about 1 percent of the value at one hour after the explosion.

(c) Another protective measure which may be undertaken is decontamination after the fallout has settled. In many situations action of some kind can be taken to reduce the amount of fallout in critical regions, e.g. on roofs of houses and in streets. The whole subject of decontamination is dealt with in Chapter 8, to which reference should be made.

Details of a provisional scheme of public control in a fallout area are set out in a Home Office Memorandum (Reference (1)). This scheme is the accepted Government policy for Civil Defence against fallout.

Two detailed aspects of protective action against fallout will be discussed in this Chapter, namely, Protective Clothing (in Section 7.7.2), and Filters (in Section 7.7.3).

References

(1) Radioactive Fallout - Provisional Scheme of Public Control. Manual of Civil Defence, Vol. I, Pamphlet No. 2 (H.M.S.O.) (Restricted)

7.6.2. Surface contamination

The radioactive contamination of ground areas by fallout material (which was discussed in Section 7.5), gives rise to hazards which may be considered from two aspects. Firstly, the direct effect of the radiation exposure on human beings who might have to live and work in a contaminated area, and secondly, the indirect effects resulting from the consumption of food grown (and animals raised) in such a region. A full discussion of the many biological problems involved would be out of place in this manual. The calculation of exposure doses from fission products has been discussed in Chapter 3, Section 3.2 (External Residual Radiations) and leads to an estimate of the time that may be spent at a given location, provided that some limit is set for the total exposure dose. However, the value of such an emergency dose will depend on the conditions existing in the particular circumstances. A discussion of some of the factors involved will be found in Reference (1).

In contaminated agricultural areas the hazard to workers could be reduced by turning over the earth so as to bury the fallout particles (see Chapter 8, Section 8.6 for further details). But there still remains the question of the absorption of fission products from the soil by plants, and their ultimate entry into the human system in food. It is known that some elements are taken up more easily than others, but the actual behaviour depends on the nature of the soil and other factors. This highly complex problem is still being studied to determine the extent of the hazard which would result from the absorption of fission products by plants in various circumstances, and how it might be minimised. For recommended limits for the ingestion of radioactive substances see Chapter Section 3.3.

Danger during the fallout will also arise from the use of ventilation systems in places where shut-down would not be practicable, e.g. control centres. Ventilation plant dealing with large air flows could draw considerable quantities of the full concentration of fallout into the buildings. Deposition of this material inside the buildings could set up a radiation as well as a possible inhalation hazard. The provision of filters to combat this risk is discussed in Section 7.7.3.

References

(1) Hazards to Man of Nuclear and Allied Radiations (Medical Research Council, H.M.S.O. 1950), especially pp. 55-60.

7.6.3. Effects of weather on contamination by fallout

A factor which might contribute to the dispersal of active material would be the penetration of fallout into porous soil so that rain might help to contaminate soil in depth, whilst at the same time leaching out some of the soluble active constituents. The results of tests in which penetration was assessed suggest that it is of no practical significance.

In a trial (Reference (1)) conducted at Suffield, Canada, month-old fission products from a pile were spread out as a solution over an earth plot. It was found that the persistence of active material was influenced more by radioactive decay than by weathering loss. Two periods of heavy rainfall were not characterised by abrupt changes in the dose rate above the plot, while samples taken after a total rainfall of more than 3.5 inches showed that almost all the active material remained in the top 3 mm. of soil. As this included a rainfall of more than one inch in three days, which must have penetrated to a considerable depth, it was concluded that the washout by rain was very slight. Since soil is such an excellent filter for water, little or no contamination of water supplies is to be expected, other than that which actually falls into surface water.

In land reclamation tests carried out after Operation 'Jangle' (Reference (2)), it was found that the contaminant lay almost entirely on the surface, and that rain, after the explosion but before the tests, did not result in any significant penetration of the soil by the contaminant. The rain did, however, inhibit the movement of surface contamination by the wind.

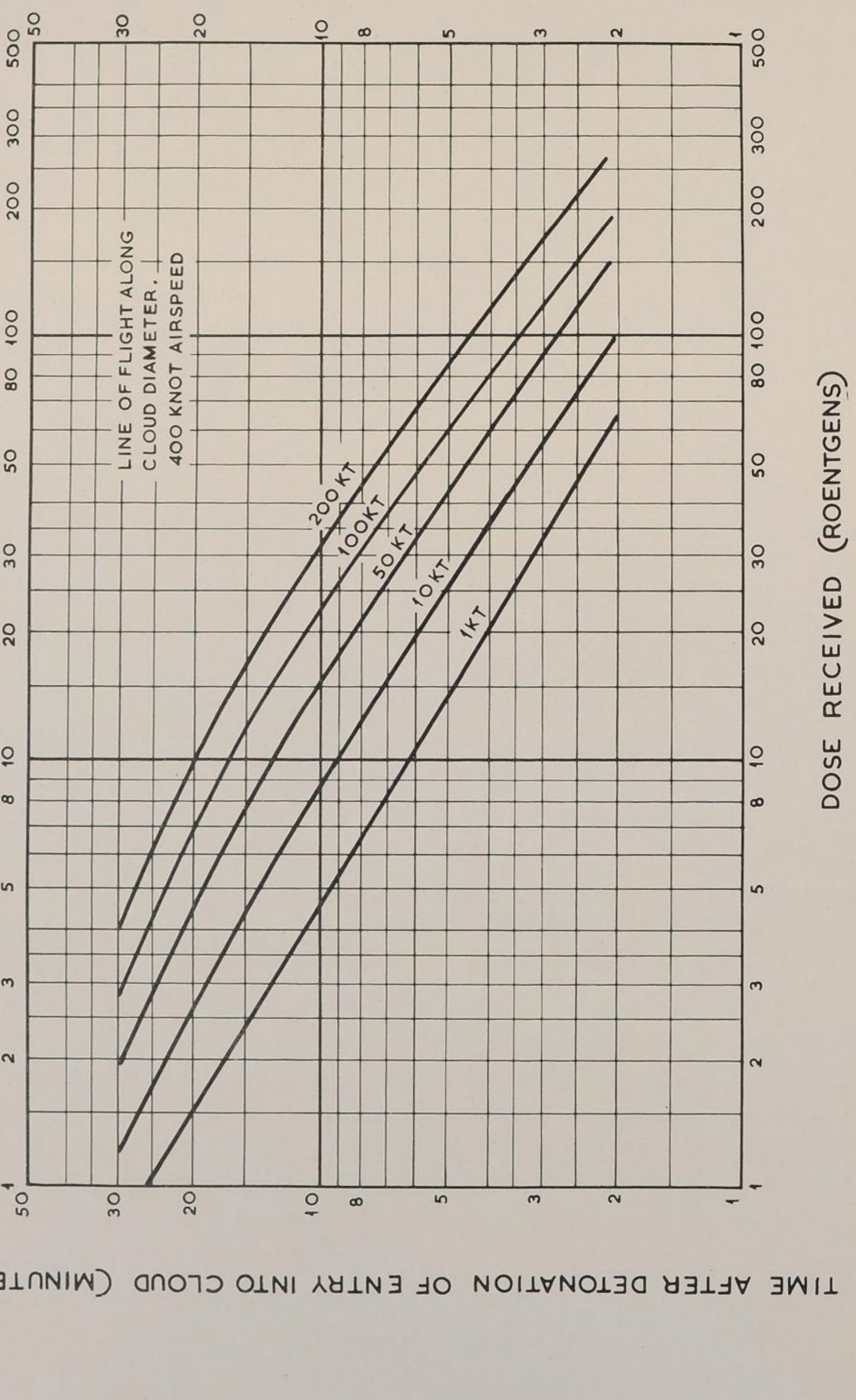
It was also observed at Operation 'Jangle' that light rain, which occurred six days after an underground burst, contributed to substantial decontamination of experimental buildings. The combined effects of wind and rain were thought in some cases to have caused building decontamination of the order of 90%.

The most spectacular effect of the weather on surface contamination noted at Operation 'Jangle' was the movement of large amounts of activity by high winds which persisted for several days after the test. Contamination near the crater area was moved downwind, and on the second day after the burst, activity levels at about a mile downwind were actually increased, in spite of decay. It is concluded that the movement of contamination from an underground or surface burst by winds could be a serious problem if dusty decontamination operations are undertaken during the first few days after a detonation. (See also Chapter 8 on Decontamination.)

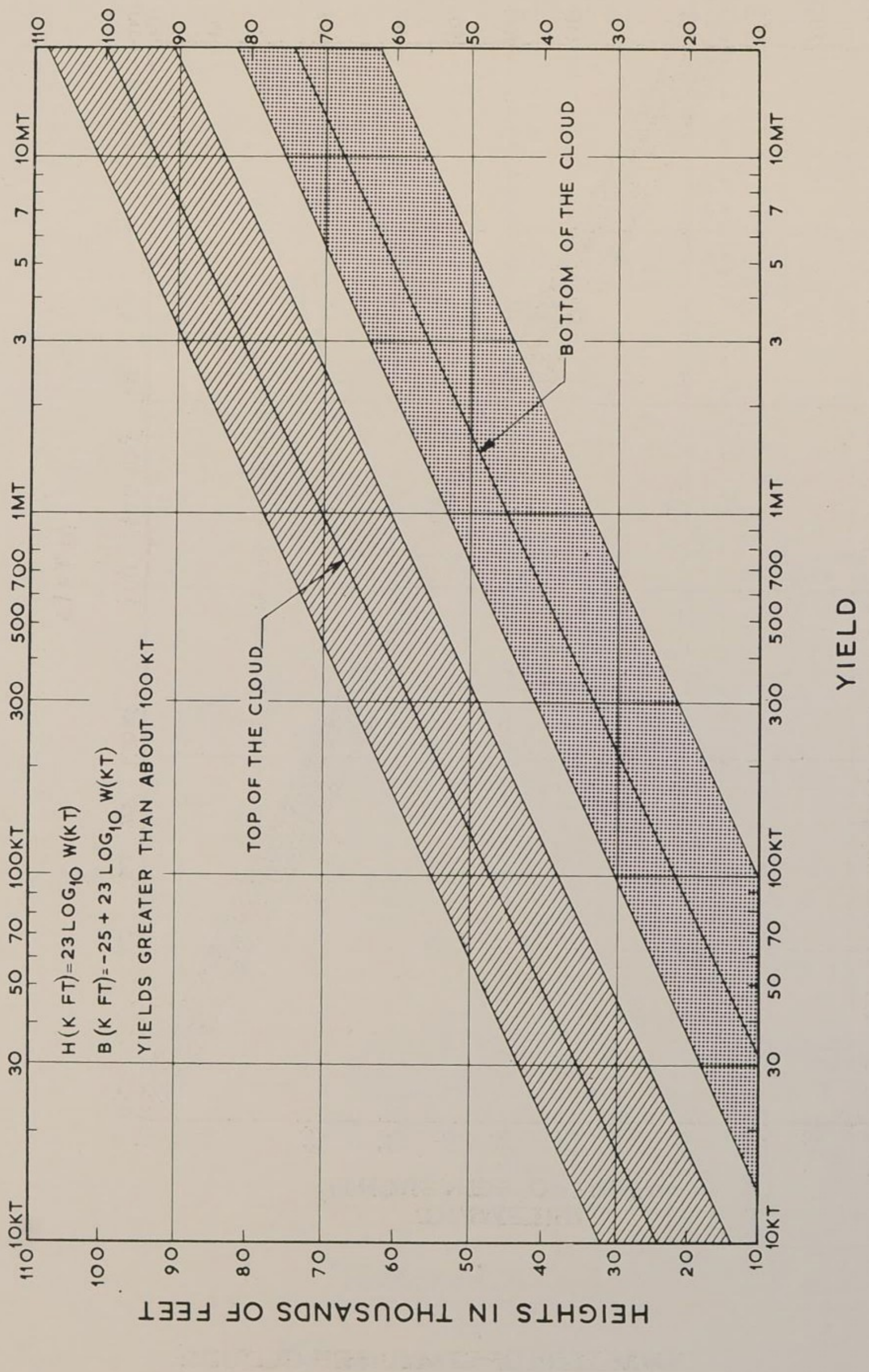
References

(1) Langstroth, G.O., Johnston, R.H., Hogg, B.G. and Fish, F.H. Suffield Technical Paper No. 18, August, 1952. (Secret)

(2) Operation 'Jangle' - U.S. Armed Forces Special Weapons Project Report No. WT-400. Project 6.2 "Protection and Decontamination of Land Targets and Vehicles". (Secret)



RADIATION DOSE RECEIVED FROM FLYING THROUGH AN ATOMIC CLOUD



DIMENSIONS OF STABILISED CLOUDS
IN CENTRAL PACIFIC

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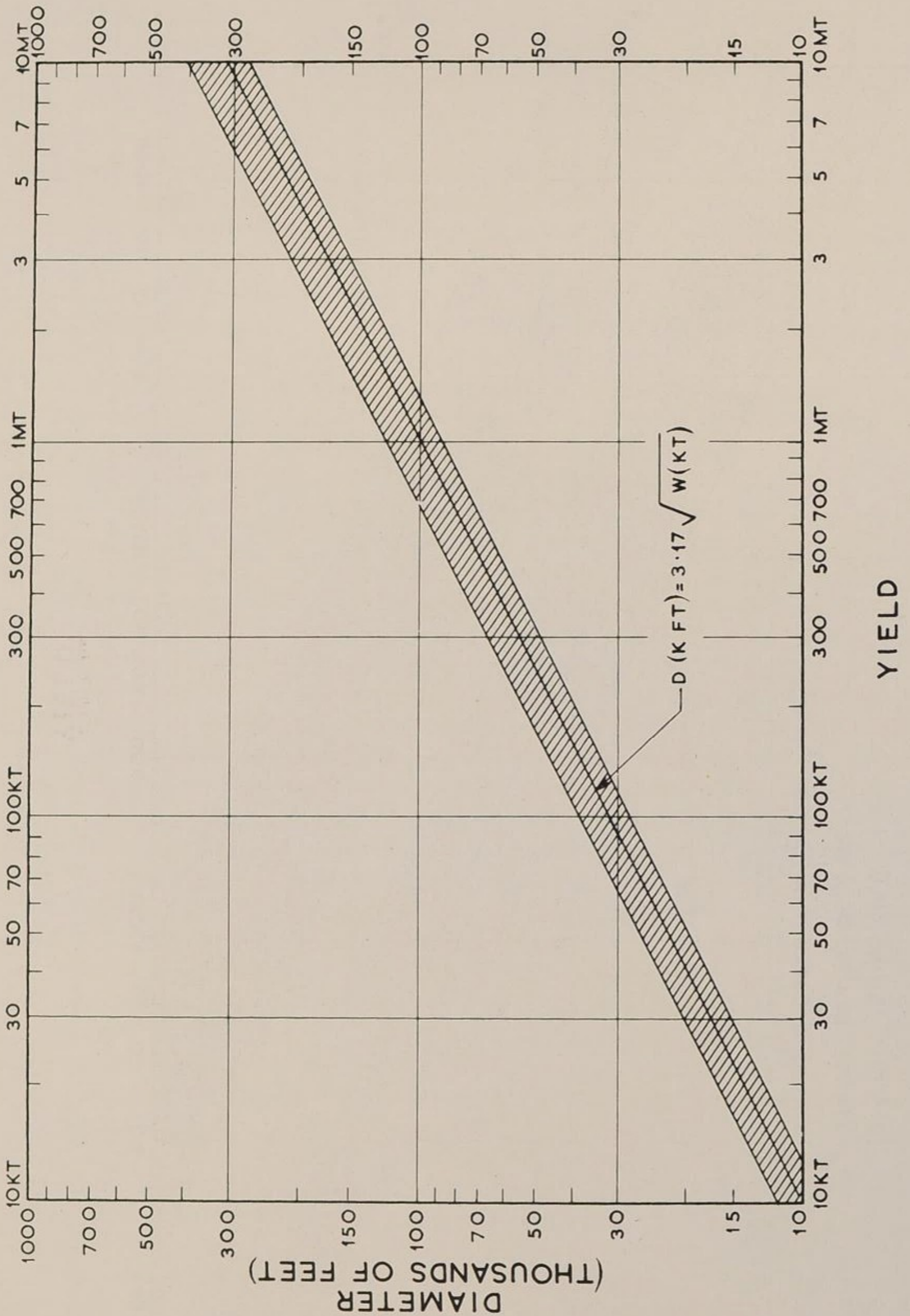

DIAMETERS OF STABILISED CLOUDS
AS A FUNCTION OF YIELD

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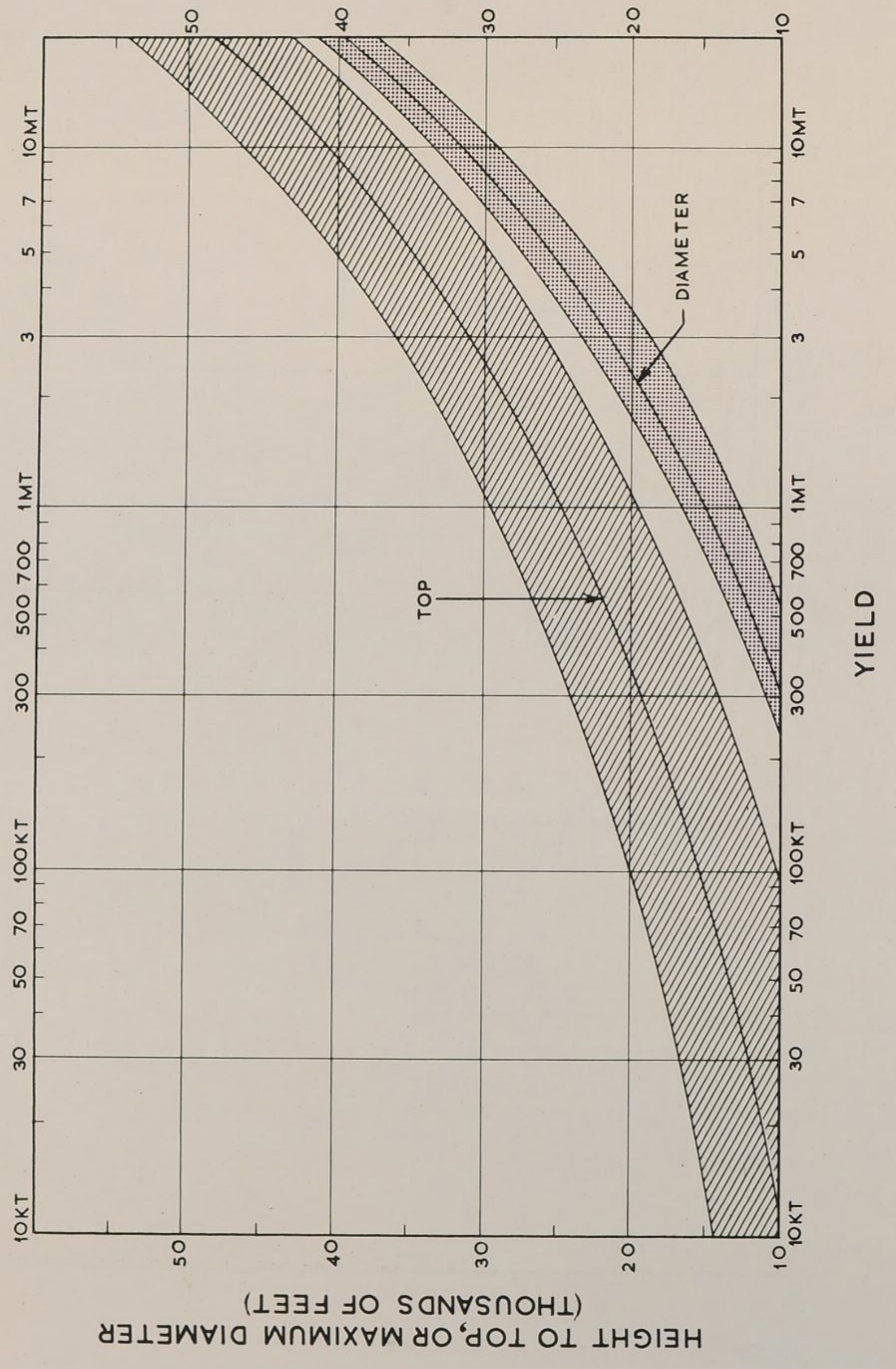

TOP AND DIAMETER OF VISIBLE
NUCLEAR CLOUDS AT 1 MINUTE

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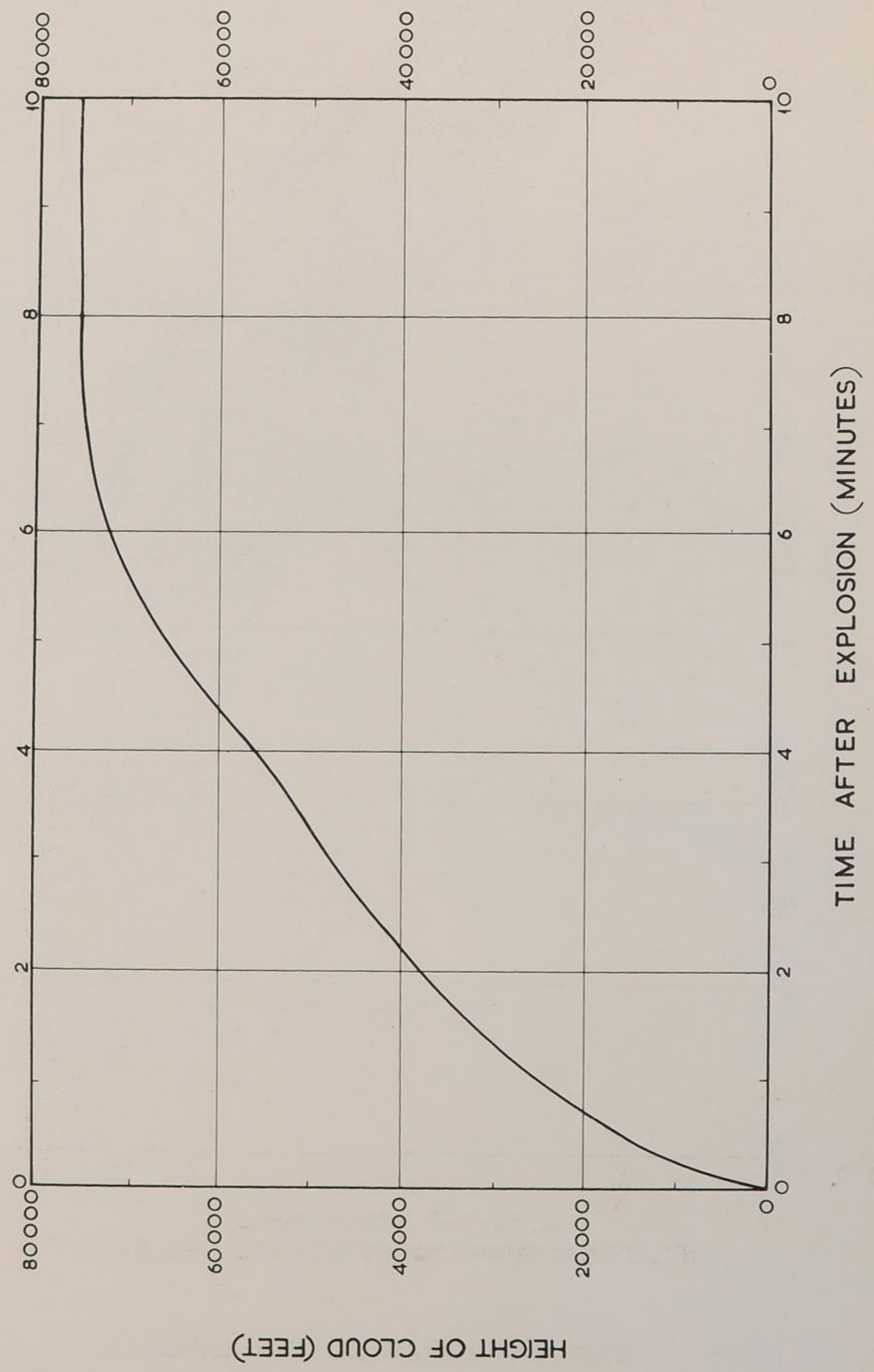
PART VII
CHAPTER 7
SECTION 7.6.1
FIGURE 1



HEIGHT OF CLOUD ABOVE BURST HEIGHT AT VARIOUS TIMES AFTER A 1-MEGATON EXPLOSION.

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7.6 Hazards from Fallout

7.6.1 Cloud contamination

Radioactive particulate clouds at high altitudes could present a serious hazard to aircrews having to fly through them. In addition to the external gamma dose received during passage through the cloud, there would be the exposure of longer duration arising from the contamination of aircraft by the deposition of activity. Contamination would also occur in the event of the radioactive cloud being drawn into the aircraft through air supply systems, e.g. cabin pressurization systems.

The speed at which the top of the radioactive cloud ascends depends on the meteorological conditions as well as on the energy yield of the bomb. An idea of the rate of rise following a 1 MT burst is given by the results in Table 1, and the curve in Figure 1, which are both taken from Reference (1). In general, the cloud will have attained a height of three miles in 30 seconds, and 4.5 miles in about 1 minute. The average rate of rise during the first minute or so is roughly 260 miles per hour.

TABLE 1

Rate of Rise of Radioactive Cloud (1 MT)

Height (miles)	Time (minutes)	Rate of Rise (miles per hr.)
2	0.3	300
4	0.75	200
6	1.4	140
10	3.8	90
14	6.3	35

The eventual height reached by the radioactive cloud depends upon the heat energy of the bomb, and upon the temperature gradient and density of the surrounding air. The greater the amount of heat liberated, the greater will be the distance the cloud ascends. It is probable however, that the maximum height attainable by an atomic cloud is affected by the height of the top of the troposphere, i.e. by the base of the stratosphere, for atomic clouds which reach this level.

As a general rule the temperature of the atmosphere decreases with increasing altitude. However, in some circumstances an inversion layer occurs, where the temperature begins to increase with altitude. If the radioactive cloud should reach such a temperature inversion layer, it will tend to spread out to some extent. Nevertheless, due to buoyancy of the hot air mass, most of the cloud will usually pass through an inversion layer.

Upon reaching a level where its density is the same as that of the surrounding air, or upon reaching the base of the stratosphere, part of the cloud slows its rise and starts to spread out horizontally. This results in the formation of the mushroom-shaped cloud that is characteristic of nuclear explosions. The maximum altitude of the bottom of the mushroom-head, which is attained within about 8-10 minutes, is generally from 5-10 miles for a large burst. The top of the cloud rises still higher, the altitude increasing with the energy yield of the explosion. It is stated in Reference (1) that in tests with devices having energies in the megaton range, carried out in the

Pacific during 1952 and 1954, the tops of the clouds rose to heights of about 25 miles. The mushroom cloud generally remains visible for about an hour before it is dispersed by the winds into the surrounding atmosphere and merges with other clouds in the sky.

Some recent information concerning the height, dimensions and rate of rise of clouds from nuclear weapons has been given by Shelton (Reference (2)).

The height to top, and the diameter, of visible nuclear clouds at 1 minute, are given in Figure 2 (Reference (2)). Only surface bursts have been plotted and the widths of the bands are only sufficiently wide to cover the existing data. The wide scatter in cloud heights for surface bursts indicates that small variations in environment can give the same effect as a variation of a factor of 5 in yield. It is further stated, in Reference (2), that radioactive clouds rise in the atmosphere and stabilise at heights proportional to the logarithm of their yields. The dimensions of stabilised clouds in the Central Pacific are shown in Figure 3. For yields greater than 100 KT the following equations apply:-

$$H = 23 \log_{10} W \qquad (7.1)$$

and $$B = -25 + 23 \log_{10} W \qquad (7.2)$$

Where H = height of top of cloud (in Kilofeet)
B = height of bottom of cloud (in Kilofeet)
W = yield in kilotons.

Diameters of stabilised clouds are proportional to the square roots of the yields, and this is illustrated by Figure 4, from which it is seen that:-

$$D = 3.17 \sqrt{W} \qquad (7.3)$$

Where D = cloud diameter (in Kilofeet)

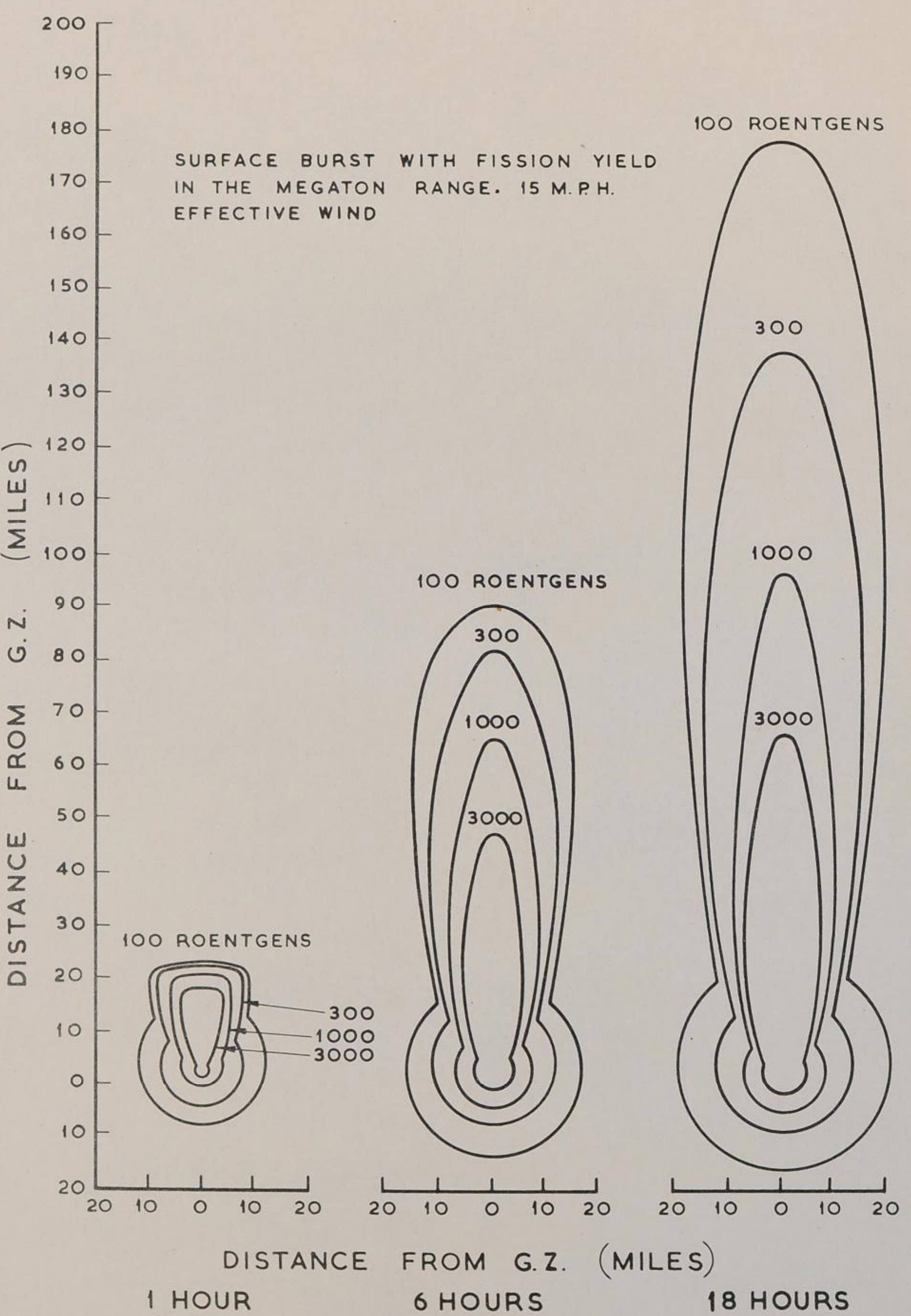
The dose received by personnel in aircraft flying through an atomic cloud at various times after detonation, may be read from Figure 5 (obtained from Reference (3)). This Figure gives the dose that is received for various weapon yields for a particular air speed, and may be converted to other air speeds by the approximate relation that if the aircraft is travelling twice as fast, its crew will receive half the dose; and if it is travelling half as fast, the crew will receive twice the dose. It should be noted however, that account does not appear to be taken of the dose from contamination collected by the aircraft.

References

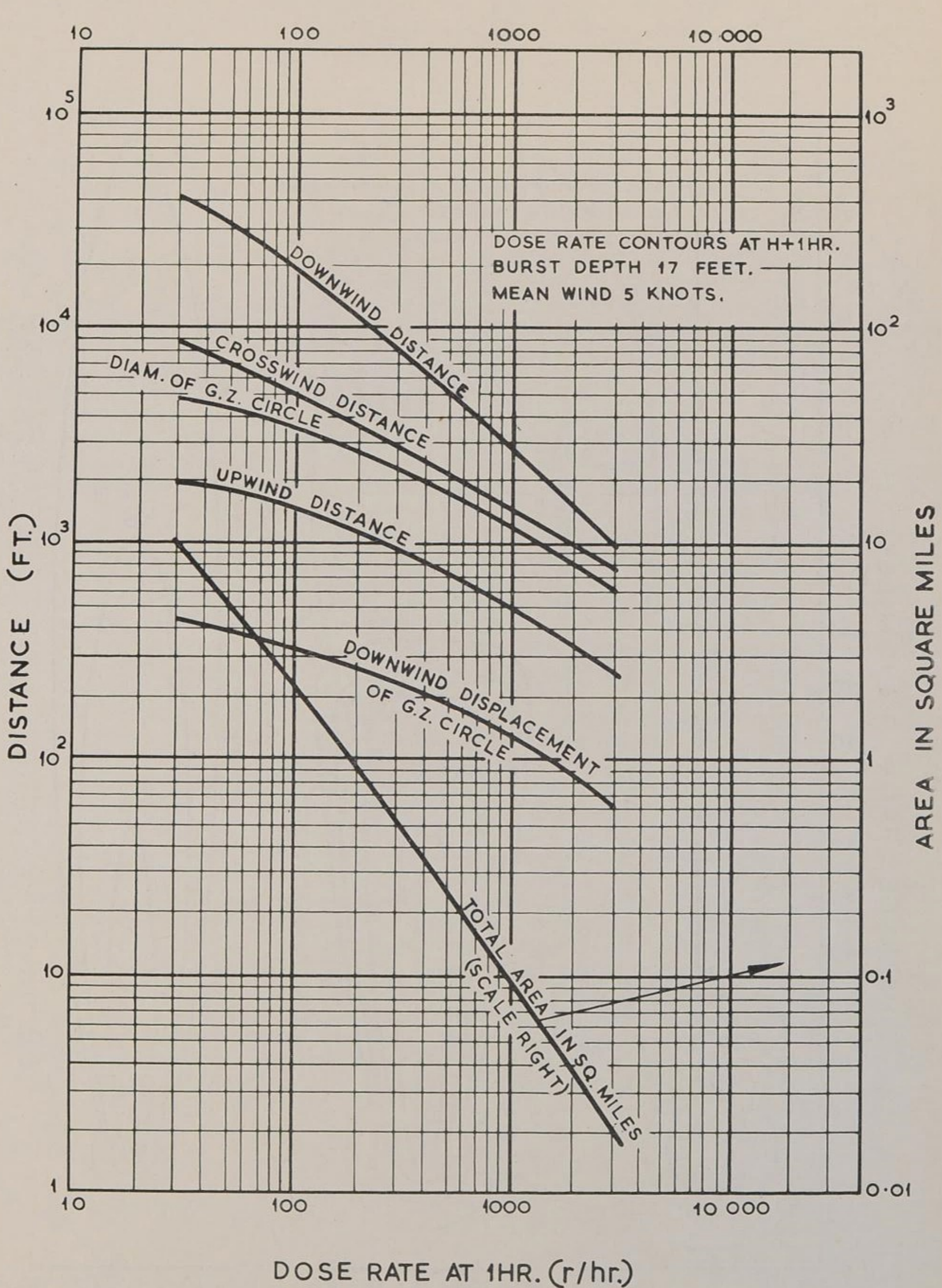
(1) Effects of Nuclear Weapons, U.S.A.E.C., 1957, pp.21 and 23.

(2) Shelton, F. H. - "The Physical Aspects of Fallout" Tripartite Conference on The Effects of Atomic Weapons, 1957.

(3) Capabilities of Atomic Weapons, 1955. A.F.S.W.P. TM-23-200 (Confidential/Atomic) Figure 29.



TOTAL (ACCUMULATED) DOSE CONTOURS FROM FALLOUT-
MEGATON SURFACE BURST



DIMENSIONS FOR CONTAMINATION PATTERNS
1KT UNDERGROUND BURST

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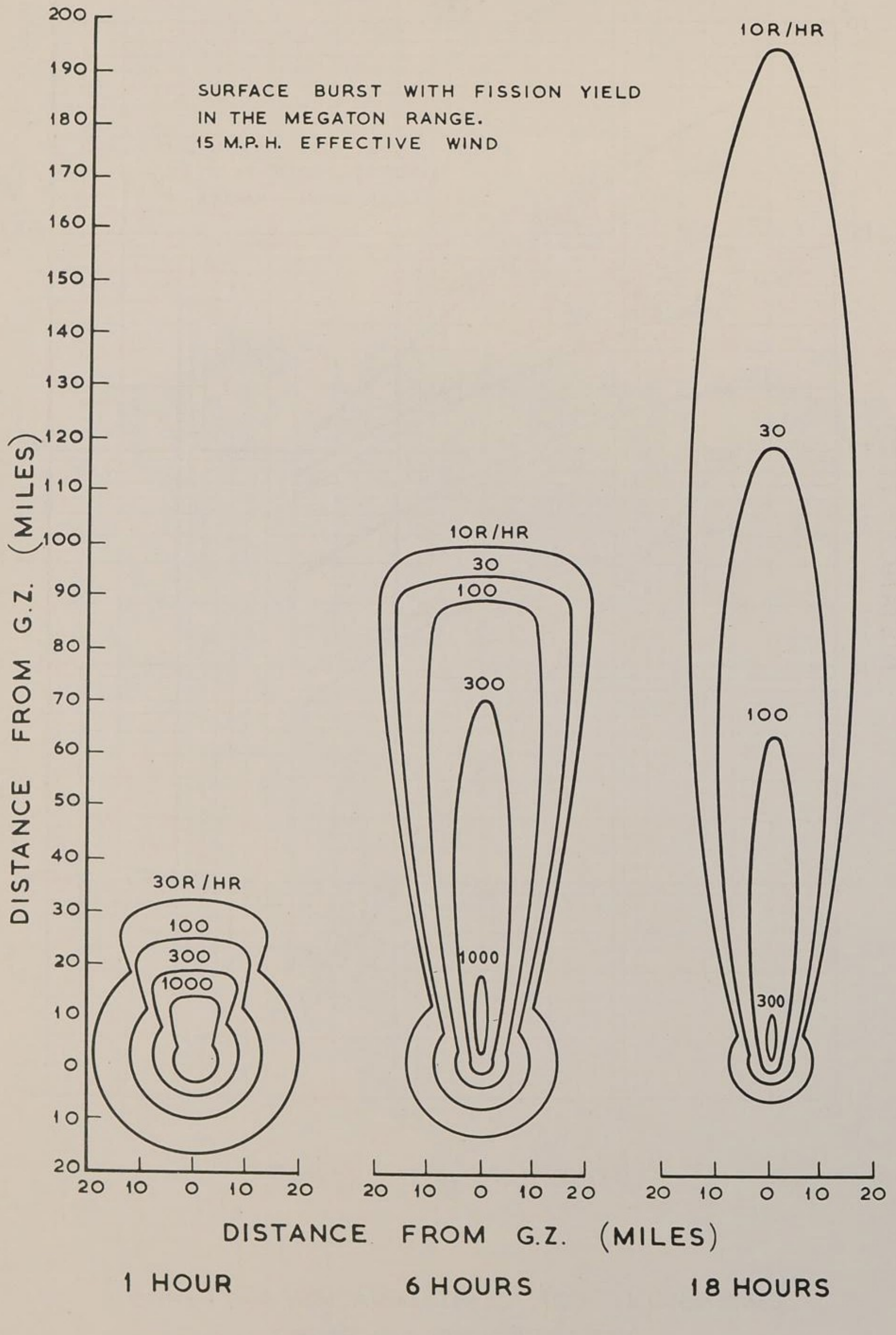

DOSE-RATE CONTOURS FROM FALLOUT—
MEGATON SURFACE BURST

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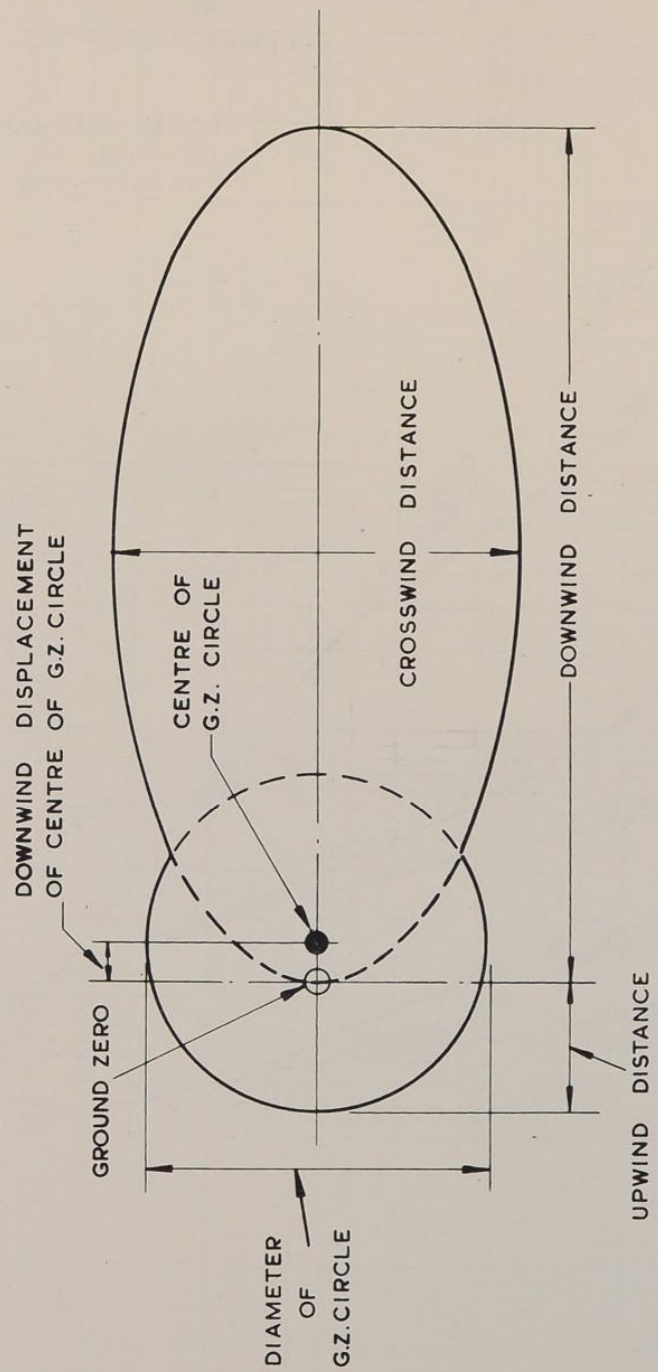

GENERALISED FALLOUT PATTERN

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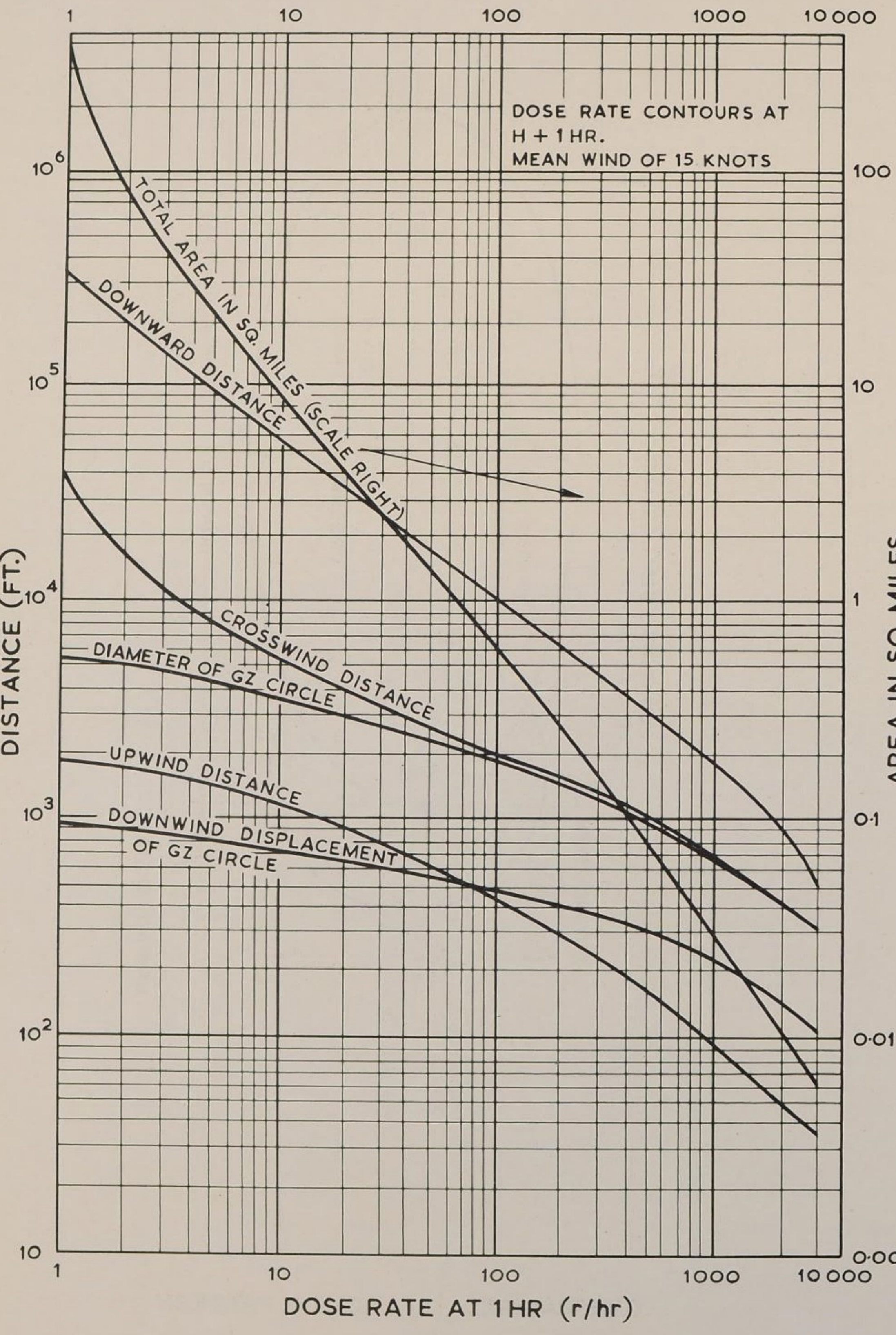

DIMENSIONS FOR CONTAMINATION PATTERNS
1 KT SURFACE BURST

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TABLE 1

Calculated Radiation Doses at Two Locations in Ronglap Atoll from Fallout Following the March 1st, 1954, Test at Bikini

Exposure period after the explosion	Accumulated dose in this period (roentgens)	
	Inhabited location	Uninhabited location
First 36 hours	140	2,150
36 hours to one week	101	1,310
One week to one month	73	950
One month to one year	83	1,080
Total to one year	397	5,490
One year to infinity	about 129	1,680

The following observations on the close-in time of arrival of fallout and the build-up of activity, are due to Shelton (Reference (3)).

Fallout from an overland surface burst of about a megaton will begin to arrive on the ground over an area the order of the size of the visible cloud, almost like a blanket, at about 15-20 minutes following detonation. Fallout from a shot of the order of a megaton on a barge in water will begin to arrive at the surface after about 30-40 minutes. These times of arrival of the first fallout are related to particle size, the land shot fallout having the larger median particle size.

A law relating the time of arrival of fallout and peak radiation intensity, has been stated by Shelton as follows:-

> If fallout begins at a given place at t_a (hours) after detonation, then the peak dose-rate will be at $2t_a$(hours) and fallout will cease at about $5t_a^{0.7}$ (where t_a in the latter case has been less than, or equal to about 13 hours).

This leads to the conclusion that the time of peak activity approaches the time that fallout ceases as the time of arrival increases.

Reference should be made to Chapter 3, Section 3.2, for details of the critical doses and contamination levels from residual radiations, and also to Chapter 7, Section 7.6, which discusses the hazards from fallout.

References

(1) Hicks, E.P. "United Kingdom Method of Predicting Fallout Beyond 10 miles - Criteria used at Maralinga".
Tripartite Conference on The Effects of Atomic Weapons, 1957.

(2) Effects of Atomic Weapons, U.S.A.E.C. 1957, Chapter 9, pp 408-427.

(3) Shelton, F.H. - "The Physical Aspects of Fallout".
Tripartite Conference on The Effects of Atomic Weapons, 1957.

(4) Residual Contamination of Plants, Animals, Soil and Water of the Marshall Islands, Two Years' following Operation Castle Fallout. U.S.N. R.D.L.- 455. NS-081-001. 15th August,1956.
(Discreet/Military Use Only).

7.5. Areas of Contamination.

Contamination from long-range fallout is world wide, but owing to its wide dispersal and slow rate of deposition it cannot be attributed to any particular incident; it arises from the gradual build-up of deposits from an increasing number of nuclear explosions. Similarly, the hazards associated with it will be due to the slow cumulative build-up of dangerous radioactive isotopes of long half-life, e.g. Strontium 90. The contamination which can be associated with a particular incident will be that arising from medium and short-range fallout, and it is the areas of such contamination that are discussed here.

As the hazards from this type of contamination arise mainly from the external radiation, it is customary to express the areas of contamination in terms of radiation dose-rates.

Because of the complex and variable factors which influence the deposition patterns it is virtually impossible to predict the detailed pattern of contamination arising from any particular explosion. However, by recourse to an idealised fallout pattern it is possible to derive nominal fallout patterns, which can then be modified in the light of practical experience. For this purpose the complicated wind structure extending from the ground to the top of the cloud is replaced by a single mean wind. The apparent velocity of the mean wind is roughly determined by averaging the scalar velocities of the resultant winds from all altitudes between the top and bottom of the stabilised bomb cloud. A resultant wind vector for a given altitude is the vector average for all wind vectors from that altitude down to the surface. Through the concept of a single mean wind, and the use of appropriate scaling factors, it is possible to compute the idealised fallout pattern corresponding to any circumstances.

A more elaborate method of predicting fallout beyond ten miles has been developed by Hicks (Reference (1)) and used at British Trials at Maralinga.

The general features of the fallout pattern are as follows. Ground contours of equal gamma dose rate consist of two overlapping curves,

(a) Ground Zero circles whose centres are displaced a short distance downwind of Ground Zero.

(b) Down-wind ellipses having one vertex at Ground Zero and major axis extending in a down-wind direction.

These features are illustrated in Figure 1.

For a given explosion, the dimensions of the Ground Zero circles and down-wind ellipses are determined by the dose-rate of which these curves are the contour. The data are thus conveniently expressed graphically, the dimensions and areas of the contamination contours being plotted against dose rate, usually referred to a time of H + 1 hours (one hour after the explosion).

The dimensions of the idealised dose-rate contours for a 1 KT surface burst fired in a mean wind of 15 knots, are given in Figure 2 (taken from M.E.A.W., Figure 6.3.1.). Corresponding data for surface bursts of other yields and wind speeds can be obtained from the following scaling laws (reference M.E.A.W, Data Sheet 6.3.3.).

(i) Variation with weapon yield. Multiply all linear dimensions and also the value of the dose rate by $W^{\frac{1}{3}}$, where W is the total yield in kilotons.

(ii) Variations with wind speed. Multiply the down-wind displacement of the Ground Zero circle and the down-wind length of the ellipse by the cube root of the wind speed ratio, i.e. by $\left(\frac{S}{15}\right)^{\frac{1}{3}}$ where S is the wind speed in knots. Divide the cross-wind breadth of the ellipse by the cube root of the wind speed ratio. The radius of the Ground Zero circle, areas of both circle and ellipse, and the value of the dose-rate on these contours, are all unchanged.

Another factor which can affect the fallout dose-rate contours is the degree of contact between the fireball and the ground. Contamination data for a 1 KT weapon exploded underground at a depth of 17 ft. in a 5-knot wind, are given in Figure 3, (taken from M.E.A.W, Figure 6.3.2.). The scaling laws stated in the previous paragraph give corresponding data for other wind speeds and yields of weapon exploded underground at a scaled depth of 17 $W^{\frac{1}{3}}$ ft.

Some indication of the manner in which the fallout pattern develops over a large area during a period of several hours following a nuclear surface burst of high yield is illustrated by Figures 4 and 5, taken from Reference (2). The mean wind velocity was taken as 15 miles per hour. Figure 4 shows a number of contours for certain arbitrary values of the dose-rate, as would actually be observed on the ground, at 1, 6 and 18 hours respectively after the explosion. A series of total or accumulated dose contours for the same times are given in Figure 5. It will be appreciated that the various dose-rates and doses change gradually from one contour line to the next. Similarly, the last contour line shown does not represent the limit of the contamination, since the dose-rate and dose will fall off steadily over a greater distance.

In general, at any given location at a distance from a surface burst, some time will elapse before the fallout arrives. This time will depend on the distance from Ground Zero, the time taken from the particles to descend to earth, and the mean wind velocity. When the fallout first arrives the exposure dose-rate is small, but it increases steadily as more and more fallout descends. In a few hours the fallout will be mainly (although not absolutely) complete, and then the radioactive decay of the fission products will be accompanied by a steady decrease in the dose-rate. Until the fallout commences, the total dose will be zero, but after its arrival, the accumulated radiation dose will increase continuously, at first rapidly and then somewhat more slowly, over a long period of time, extending for many months and even years (see Table 1, taken from Reference (2)).

7.4. Radioactivity of Fallout

The radioactivity distributed amongst the particulate matter will depend on the size and also on the type of weapon. Data on the distribution of the activity in the form of radioactive particles are very limited, but there is evidence, based on the analysis of samples corresponding to long range fallout, i.e. samples consisting mainly of spherical particles and with maximum diameter about 20 microns, that specific activity generally decreases with increasing particle size.

As more and more data are accumulated on the characteristics of fallout from nuclear tests, it is becoming increasingly evident that there is a quantitative correlation between particle size and specific activity only in the case of air bursts, i.e. where no dilution with inert material occurs. No such correlation is likely to be found in the case of ground burst weapons.

As would be expected, significant differences have been found in the specific activity of particles of the same size from different explosions, e.g. the specific activity of 6-micron diameter particles expressed as d.p.m./d^3, where d.p.m. is the number of disintegrations per minute and d is the particle diameter in microns, has been found to vary between a low value of 0.3 and a high value of 50 at a time of 25 days after burst. Even in a given sample the specific activity of particles of the same size has been found to vary as much as about thirtyfold.

Further studies may reveal some factor of general application relating activity with particle size, but at present no conclusions of value to target response problems may be drawn.

7.3. Effect of Particle Size on Dispersion and Deposition

The dimensions of the cloud, its height and its movement are controlled by the size of the weapon, by the type and site of the burst and by the prevailing weather conditions, while the deposition of the particles from it is also dependent on the size distribution of the particles throughout the airborne particulate material. The dispersion and deposition patterns can be divided into three main groups based on a classification of particles as fine, medium and large, and giving rise to long, medium and short range of fallout respectively.

Fine particles are carried to considerable heights and in the case of megaton weapons a large proportion may pass into the stratosphere. The particles from the troposphere also settle very slowly but their deposition may be accelerated through scavenging by rain. It has been estimated that it takes about a month for particles to be deposited from the troposphere, and also that it takes on average about seven years for half the particles in the stratosphere to find their way into the troposphere. Two patterns for the deposition of fine particles are possible. When the particles are confined to the troposphere they will, during the comparatively short deposition time, be carried round the earth and eventually be deposited as a broad band at the latitude of burst. On the other hand particles which are carried into the stratosphere will be widely dispersed before they return to the troposphere and will eventually be deposited at the rate of about 10 percent every year over the surface of the earth.

Medium sized particles are those with moderate settling speeds. While settling they will be carried by the down wind, with some crosswind spread, and so will be deposited in elongated cigar-shaped patterns downwind of ground zero.

Large particles settle very quickly and consequently are not widely dispersed before deposition. They are composed of material from the ground carried upwards by the explosion and are derived mainly from the mushroom stem associated with ground or near ground bursts. They are found deposited in a roughly circular pattern within comparatively short distances of ground zero.

The patterns of deposition are considered in greater detail in Section 7.5.

Only in the case of a true air burst are the particles likely to cover a comparatively narrow size range; in all other cases the particulate matter will cover a very wide range of sizes.

The distinction drawn at the beginning of this section between the three types of fallout cannot be sharp, and there will be some overlap of particle size range but, as they are based on a rough size classification, it is convenient to consider particle size distributions in terms of the fallout pattern.

Composition of long range fallout

Results are based on the analysis of samples collected by aircraft equipped with special sampling filters. Some clouds have been sampled at a considerable height shortly after burst, and also after travelling thousands of miles, while others have been sampled only at long distances from ground zero. No particles larger than about 20 microns diameter have been found in any of the samples. Although the size range of particles is known in general terms, data for mass distribution of particles visible under the optical microscope are available in only one case. A sample from an air burst in which activity was found to be proportional to volume of the particles gave the approximate mass distribution, based on activity measurements, as:

Diameter Range (microns)	0 - 3	3 - 6	6 - 9
% Mass in Range	30	30	30

This distribution, together with about 10% of the mass in the diameter range 9 - 30 microns may be regarded as being fairly typical of long range fallout.

Composition of medium range fallout

The smallest particles in this type of fallout will overlap the largest particles in the long range fallout, but it is not expected that an appreciable mass of medium range fallout will consist of particles less than about 10 microns diameter. A theoretical analysis of fallout has indicated that most of the contamination downwind of the position of deposition of 300 microns diameter particles comes from the cloud and not from the stem, and this diameter may be taken as the top size in medium range fallout.

Particles in medium range fallout will therefore cover the approximate diameter range 10 - 300 microns, but the overall distribution of sizes within this diameter range will depend on all the factors influencing the formation of the particulate cloud which have already been mentioned. Gradation of sizes will also take place downwind along the track of the fallout, the larger particles settling first, and the actual distribution of sizes downwind will not follow a pattern that can be predicted with any precision.

By analysing the very limited data for the cloud from a ground burst megaton weapon a few hours after burst, and those for actual deposits on the ground from this and other ground burst kiloton weapons, it has been possible to derive a size analysis which indicates the type of overall distribution to be expected in medium range fallout. This is:-

Diameter range (microns)	0-5	5-10	10-20	20-30	30-40	40-50	50-60	60-80	80-100	>100
% Mass in range	1.0	2.0	7	12	18	15	12	15	8	10

Composition of short range fallout

Particles deposited as short range fallout have sizes from about 300 microns diameter to the largest particles falling from the mushroom stem. It is not possible to set an upper limit to the size, nor to state a size distribution. Radioactive particles several mm in diameter have been found in column fallout.

References

(1) The Effects of Nuclear Weapons. USAEC. 1957.

(2) Operation Greenhouse. Scientific Directors Report, Annex 4.6. Atmospheric Conductivity. Air Force Cambridge Research Centre Report WT-71, Sept. 1951. (Secret)

(3) Radioactive Fallout and Radiostrontium. Dr. Willard F Libby, USAEC. A.E.C. Press Release January 19th, 1956.

(4) The Nature of Atmospheric Dust. Radioactive and Electron Microscope Measurements on Fallout on Princeton, N.J., 1954-5. Heininger and Turkevitch. TIL P65414.

CHAPTER 7 - PARTICULATE CLOUDS FROM NUCLEAR WEAPONS

7.1. Introduction

Particulate matter produced in a nuclear explosion may give rise to radioactive hazards:-

(a) as an airborne cloud

(b) after deposition on the ground as fallout

(c) on re-dispersal, for example during decontamination operations.

The formation of this particulate matter will depend on the nature and size of the weapon, and on the site of the explosion; its subsequent history will be largely influenced by the prevailing meteorological conditions. Because of these complex and variable factors it is not possible to predict accurately the behaviour of the particulate matter in any one incident. It is possible, however, to give a general account of the properties of particulate clouds produced by nuclear weapons and to estimate the magnitude of the hazards associated with them.

It is the intention in this chapter, therefore, to present a broad outline of the formation, despersion and deposition of the particles in clouds, and to examine, with the aid of such information as is available, the special problems arising from the radioactivity of the particulate matter from nuclear weapons.

7.2. Formation

The radioactivity of the particulate matter associated with a nuclear explosion arises from the fission products and neutron absorption products of any tamper present. The active products are vaporised with any other material enclosed within the fireball, and as the fireball rises and cools, they condense to form the radioactive particles. Depending on the conditions and type of burst the active products may condense to form spherical particles with activity distributed throughout the particles, or in condensing, some may become associated with inactive material to form radioactive particles of various shapes and sizes, with the activity distributed in various ways. Some particulate matter associated with the burst may not be affected by the condensation of the fission products and the cloud may therefore contain both active and inactive particles.

In an air burst, the bomb debris, consisting largely of active material, condenses into very small solid particles. In this finely divided state a portion of the radioactive particles enter the stratosphere and remain suspended for several years, circulating the earth several times before reaching the surface. During this period they will decay, so that when they reach the earth's surface they will be widely dispersed and their radioactivity will be very greatly reduced, although they will still not be innocuous.

In certain weather conditions, e.g. a warm front rainfall situation, there might be appreciable fallout of a localised character owing to particles of bomb residue attaching themselves to water droplets which subsequently fall as rain. (See also Chapter 3, Section 3.2.).

An air burst of a small yield weapon would not be accompanied by serious local fallout except under special conditions such as the rainfall situation mentioned above. This is confirmed by the fact that there were no casualties in the nuclear bombing of Japan that could be attributed to residual radiation. Observations made at tests indicate that the local fallout from air bursts is also small for large yield weapons - Reference (1).

In a surface burst however, large amounts of earth, dust and debris are taken up into the fireball and ascend with it in its early stages. The material within the fireball is fused or vaporised and becomes intimately mixed with the active material, so that on cooling a very great number of contaminated particles is produced.

Other material which is sucked up with the fireball, but is not exposed to the highest temperatures, may not even be fused, although it will become contaminated with particles of condensed active products.

The larger particles, which would include a great deal of contaminated material scoured and thrown out of the crater, will not be carried up into the mushroom cloud, but will descend from the column. With some soils a base surge may be formed. Provided the wind is not excessive, this large particulate material will fall to form a roughly circular pattern around ground zero. This material will descend within a short time, not more than an hour or so from the time of burst. The smaller particles present in the atomic column are, however, carried upwards to a height of several miles, and may spread out some distance in the mushroom cloud before they begin to descend. The dispersion of these particles is considered in Section 7.3.

References

(1) The Effects of Nuclear Weapons, U.S.A.E.C., 1957, p. 49, p. 409.

6.5. Protection Afforded by Clothing

Ordinary temperate zone clothing provides negligible protection against extermal gamma radiation, considerable protection against the lower energy beta radiations, and complete protection against alpha particles. Its value in the cases of beta and alpha emitters depends largely on the extent to which it can keep the radioactive particles away from contact with the skin. Particular care must be taken to avoid the risks of fallout material being rubbed into the skin at the edges of clothing as at neck, wrists and ankles. A detailed discussion of the design considerations for protective clothing will be found in Chapter 7, Section 7.7.2.

6.6. Shielding by Vehicles

Considerable shielding is afforded in armoured vehicles required to operate through areas contaminated by residual radiation. The integral dose received by crew members, in general, is less than 10 per cent of the dose that would be received outside the vehicles. Personnel riding on the mudguards of vehicles will receive, roughly half the dose they would receive if they were on foot (Reference (1)).

Reference

(1) Operation Jangle - U.S. Armed Forces Special Weapons Project Report No. WT-400. (Secret)

6.4. Shielding by Some Common Structures

Measurements of the protection afforded by model houses against residual radiation were obtained at Operation Buffalo, and are reported in Reference (1).

Calculations on the shielding value of slit trenches against nuclear radiations are given in Reference (2).

Some measure of protection to roadways and open areas may be given by the erection of suitable earth barriers. This is discussed in Chapter 8, Section 8.3.6.

The protection afforded by a building or shelter against gamma-radiation from fallout may be expressed as the "protective factor". This is defined as the factor by which the dose rate received by a person in the building is reduced, compared with that received by a person standing in the open, or more accurately, on an infinite flat plane.

Two main difficulties arise in any attempt to calculate accurately the protective factors of buildings and shelters in general. The first difficulty is the complexity of the geometry involved (owing to the presence of doors, windows, chimney breasts, etc.) and the second concerns the uncertainty of the actual distribution of fallout material on the roof and walls of the building. Irregularities in fallout distribution on these areas are likely to arise from the slope and nature of the surface, and also from the effects of wind and weather.

A simple and rapid method of making a rough assessment of the protective factors of buildings and shelters is given in Reference (3). The basis of this scheme is to carry out the initial calculation in terms of an arbitrary "points scheme", awarding 1,000 points to a completely unprotected location (i.e. an infinite flat plane) and reducing the points for other situations in direct proportion to their protective factors. Thus, once the "points" value of a particular building have been calculated, its protective factor is given by:-

$$\text{Protective factor} = \frac{1{,}000}{\text{"Points" value}}$$

Separate consideration is given, and appropriate "points" calculated, for the radiation coming from each of five directions, that is, from the roof and the four walls. For each of these directions the "geometrical" points are first determined, that is the points which derive solely from the distance factor and depend on the size and height of the building. These "geometrical" points are then multiplied by the attenuation fraction resulting from the shielding material between the shelter and the fallout, to give the total roof or wall points as the case may be. These five sets of points are then added up to give the final value for the accommodation.

An assessment of the accuracy of the method has been obtained by comparing calculated values for protective factors with those given by field experiments using radioactive sources. It is concluded that:-

(i) Where the geometry of the shelter is simple (e.g. a brick surface shelter) results given by the points scheme should not be in error by more than 50 percent, and may be considerably better.

(ii) For complicated structures (e.g. the ground floor of a 19th century Government building), results given by the points scheme may be in error by a factor of 3 or 4. In these complicated cases the points scheme tends to under-estimate the protection given, so that results given by this scheme should be at least on the safe side.

See Reference (4) for the published version of this technique, with worked examples.

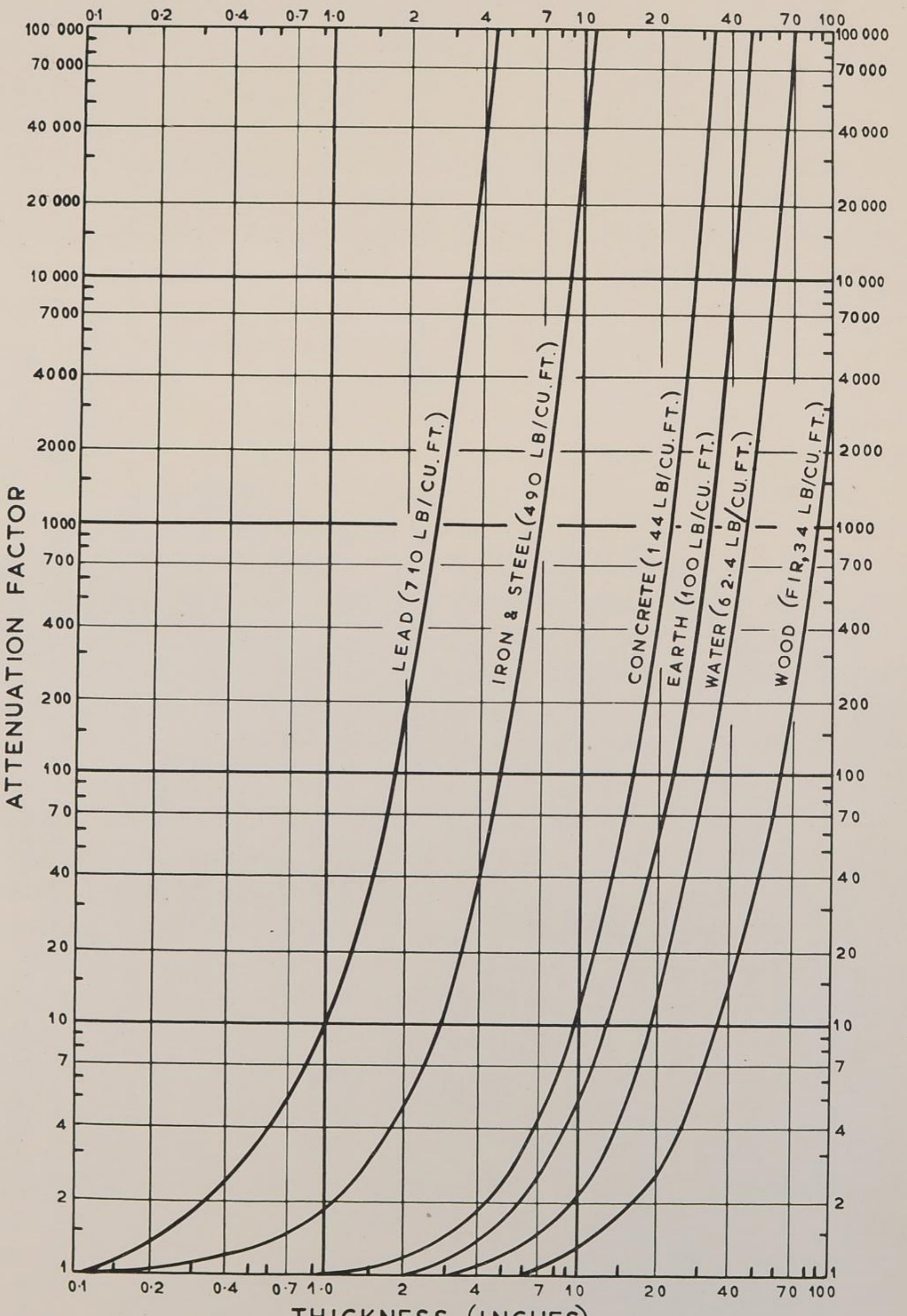
References

(1) Tripartite Conference Report TCR 7/57 by A.M. Western (Confidential) (To be published later as an A.W.R.E. Report).

(2) A.O.R.G. Report No. 12/55 - "The Protective Value to Personnel of Slit Trenches against Thermal and Gamma Radiation Effects of Nuclear Explosions. (Secret/U.K. Eyes Only)

(3) Home Office Report CD/SA 68, 1956 - "Protection Against Gamma-Radiation from Fallout" (Confidential)

(4) Home Office Publication "Assessment of the Protection Afforded by Buildings against Gamma-Radiation from Fallout", (1957). H.M.S.O.



ATTENUATION OF FISSION PRODUCT RADIATION

6.3. Shielding from Residual Gamma-Radiation

The mechanism by which this radiation interacts with matter are the same as those described for initial gamma-radiation. Attenuation factors for various shields can be calculated from Figure 1, Section 5.1.4 of Chapter 5, on Shielding against initial gamma-radiation, but a lower mean energy will be appropriate. In this matter there is no evidence of any difference between kiloton weapons and megaton weapons. An average energy of 0.7 Mev has been recommended (Reference (1) p.402), but calculation (Reference (2)) suggests that for thick shields (greater than 9 inches of concrete) 1 Mev may be better when calculations are done by the modified upper limit method (Reference(3)). The low energies of the radiation increase the complications of calculating from first principles because of air scattering effects. Figure 1 taken from Reference (1) p.403, gives values for the attenuation of residual gamma-radiation by various materials. It should be noted however that these curves (which are similar to those given in Figure 70 of Reference (4)), do not agree with the half-thickness values quoted in Table 9.35 page 402, of Reference (1). For example, the half-value thickness for concrete in the figure is read off as 4.5 inches, whereas in Table 9.35 it is given as 2.2 inches. In British Trials a figure of 2.3 inches was obtained, and the U.S. figure of 4.5 inches would therefore seem to be an error.

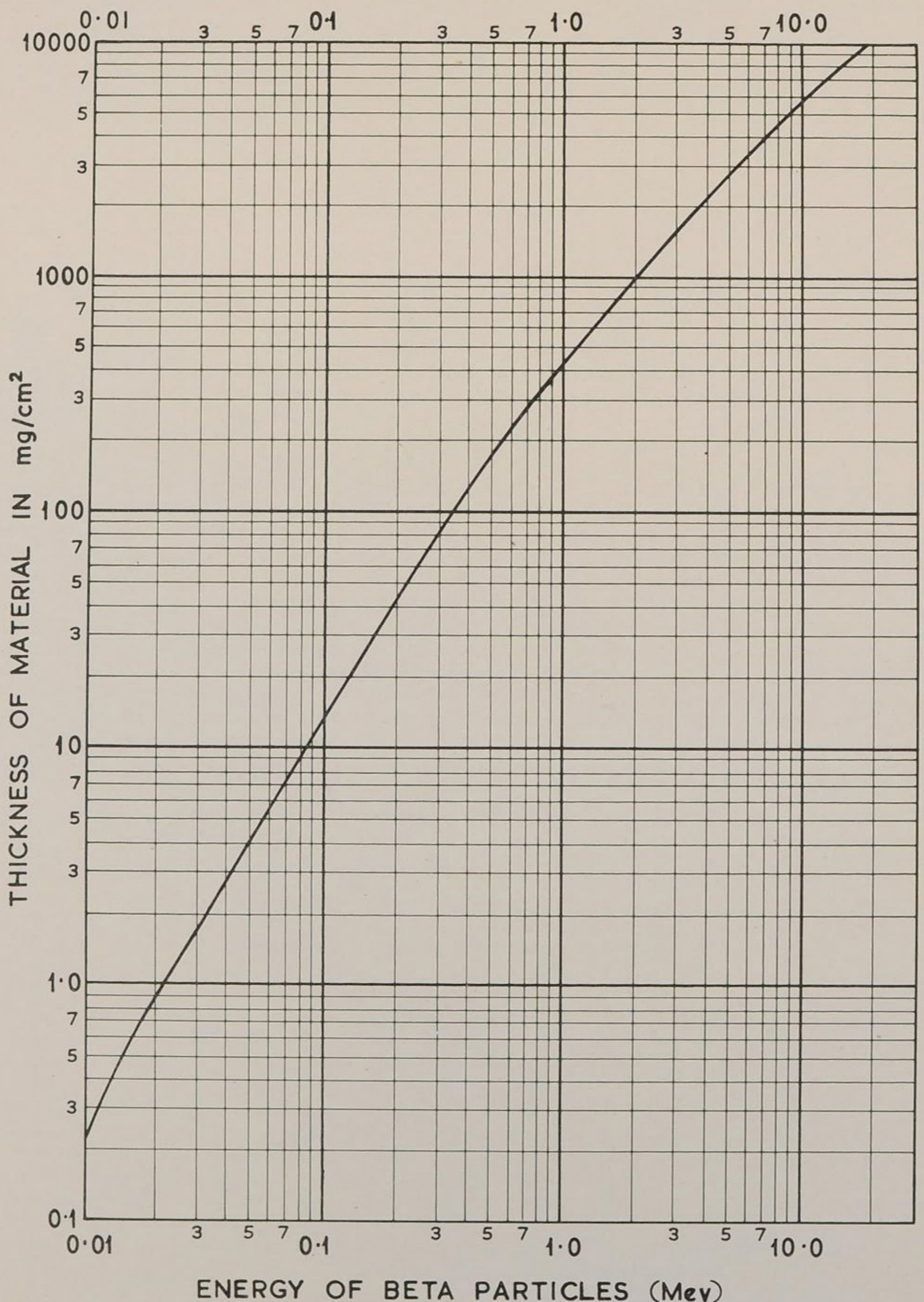
References

(1) The Effects of Nuclear Weapons, U.S. Atomic Energy Commission, 1957.

(2) Home Office Report CD/SA 62, 1955.

(3) Ministry of Supply, H.E.R. Report No. H13/51, 1951, "Tables for the Solution of Gamma-Ray Shielding Problems". (Restricted)

(4) Capabilities of Atomic Weapons, A.F.S.W.P. TM23-200 (1955) (Confidential/Atomic)



RANGES OF BETA PARTICLES

6.2. Shielding from Residual Beta-Radiation

The ranges of beta particles in matter are shown in Figure 1. Except in the early stages after the explosion (up to an hour or two), there are no radioactive explosion products emitting beta particles of more than about 3 Mev energy and most of them emit beta particles of 2 Mev or less. Study of Figure 1 shows that shielding against beta particles is quite an easy matter, and most ordinary structures (buildings, aircraft, vehicles, thick clothing, etc.) are enough to keep out all or most of the beta particles from explosion products. Of course, further protection may be needed against beta emitting substances which may drift or be blown through gaps in structures such as windows, ventilators, etc.

CHAPTER 6 - SHIELDING FROM RESIDUAL RADIATION

6.1 Introduction

A description of the nature and origin of the residual radiation from a nuclear weapon is given in Chapter 6 of Reference (1). An unclassified account will be found in Chapter 9, Reference (2).

The residual nuclear radiation is defined as that emitted after one minute from the instant of a nuclear explosion. This radiation arises mainly from the bomb residues, that is, from fission products and, to a lesser extent from the uranium and plutonium which have escaped fission. In addition, the residues will usually contain some radioactive isotopes formed as a result of neutron capture by the bomb materials. Another source of residual nuclear radiation is the activity induced by neutrons captured in various elements present in the earth, in the sea, or in substances which may be in the explosion environment (see Chapter 3, Section 3.2 for further details of neutron-induced activity).

In the case of an air burst, particularly when the ball of fire is well above the earth's surface, a fairly sharp distinction can be made between the initial and the residual nuclear radiation. The reason is that by the end of a minute essentially all the bomb residues, in the form of very small particles, will have risen to such a height that the nuclear radiations no longer reach the ground in significant amounts. Subsequently, the fine particles are widely dispersed in the atmosphere and descend to earth very slowly. With surface, and especially sub-surface explosions, the demarcation between initial and residual nuclear radiations is not as definite. Some of the radiations from the bomb residues will be within range of the earth's surface at all times, so that the initial and residual categories merge continuously into one another. For very deep underground and underwater bursts, the initial gamma rays and neutrons produced in the fission process may be ignored. Essentially, the only nuclear radiation of importance is that arising from the bomb residues. It can, consequently, be treated as consisting exclusively of the residual radiation. In a surface burst however, both initial and residual nuclear radiations must be taken into consideration.

The fission products constitute a very complex mixture of some 200 different isotopes of 35 elements. Most of these isotopes are radioactive, decaying by the emission of beta particles, frequently accompanied by gamma radiation. About 0.11 pounds of fission products are formed for each kiloton (or 110 lb. per megaton) of fission energy yield. The total radioactivity of the fission products initially is extremely large, but it falls off at a fairly rapid rate as a result of decay.

At one minute after a nuclear explosion the radioactivity from the 0.11 lb. of fission products from a 1-kiloton explosion is of the order of 10^5 megacuries.

Some indication of the rate at which the fission product radioactivity decreases with time may be obtained from the following approximate rule:-

> For every 7-fold increase in time after the explosion, the activity decreases by a factor of 10. For example, if the radiation intensity at one hour after the explosion is taken as a reference point, then at 7 hours after the explosion the intensity will have decreased to one-tenth; at 7 x 7 = 49 hours (or roughly two days) it will be one-hundredth; and at 7 x 7 x 7 = 343 hours (or roughly two weeks), the activity will be one-thousandth of that at one hour after the burst.

Another aspect of the rule is that at the end of one week (7 days), the radiation will be one-tenth of the value after one day. This rule is roughly applicable for about 200 days, after which time the radiation intensity decreases at a more rapid rate. (Reference should be made to Chapter 3, Section 3.2, for information on dose-rates from residual nuclear radiations.)

In the residual radiation period, there is no emission of neutrons, but once the debris reaches the ground there is a hazard from alpha and beta particles as well as from gamma radiation from the radioactive explosion products. Alpha particles, with a range of only a few centimetres in air, are hazardous only when taken into the body or when contamination is directly on the skin. Consequently, no special shielding need be prepared against alpha emitters; clothing which is effective against beta particles will be more than adequate to exclude alpha particles.

References

(1) Manual on the Effects of Atomic Weapons, A.W.R.E. (1955)
(Secret/Atomic/U.K. Eyes Only)

(2) Effects of Nuclear Weapons, U.S.A.E.C., 1957.

5.2.7 Neutron shielding

Very little experimental information is available on the effectiveness of shields against the neutrons from a nuclear explosion. It is stated in Reference (1) that 10 inches of concrete will reduce the neutron dose by a factor of 10. Until more measurements have been made it is necessary to deduce the probable behaviour of shielding materials which might be used in practice from the available neutron cross section data.

In order to minimise the build-up factor a shield should be made of elements which have large sections for capture followed by emission of charged particles or radiation for the energies present in the incident neutron flux. In general it is not possible to make such a shield against a neutron source with an extended spectrum. All that can be done is to include a large proportion of light elements in the shield, so that, although the build-up factor will be large for thick shields, the energy of fast neutrons - and hence their lethality - will be considerably reduced at each collision. The average number of collisions in an element with relative efficiency η (hydrogen = 1) required to slow down a neutron from energy E_1 to energy E_2 is:

$$N_{E_2}^{E_1} = \eta \ln \frac{E_1}{E_2} \qquad (5.2.4)$$

The values of η for various common elements are shown in Table 1, together with the average number of collisions required to slow down 3 Mev neutrons to (a) thermal energies (N_{th}) where the probability of radiative capture (n, γ) is large, and (b) 10 Kev energy ($N_{10\ Kev}$) where the lethality ceases to decrease appreciably as the energy is further reduced.

TABLE 1

Relative Efficiencies of Various Elements as Absorbers of 3 Mev Neutrons

Element	H	B	C	N	O	Na	Si	Ca	Fe
η	1	0.18	0.155	0.132	0.120	0.085	0.070	0.049	0.035
N_{th}	18.6	103	120	141	155	219	266	380	530
$N_{10\ Kev}$	5.7	32	37	43	48	67	82	119	163

The average distance travelled by a neutron in a particular direction ($\bar{R}$) after N elastic collisions is given (in the case where scattering is isotropic in the centre of mass system) by:

$$\bar{R} = \sqrt{\frac{2N}{1 - \frac{2}{3A}}}\cdot \lambda \qquad (5.2.5)$$

where λ is the mean free path and A is the atomic weight of the scattering nucleus. Combining equations (5.2.4) and (5.2.5) will give the average thickness of an absorber required to slow down neutrons from energy E_1 to E_2. The factor $(1 - \frac{2}{3A})^{-\frac{1}{2}}$ allows for the tendency a neutron has to be scattered forward in the "shield system" when scattering is isotropic in the centre of mass system. This tendency is much smaller than that shown by Compton

scattered gamma-rays (namely 50 per cent of sçatter within 20° of the original direction at 3 Mev), and the factor $(1 - \frac{2}{3A})^{-\frac{1}{2}}$ can usually be ignored for all common elements except hydrogen.

The effect of absorbing neutrons in a few common materials is now considered.

(i) Air - This is considered as 80 per cent nitrogen and 20 per cent oxygen, the other elements present being neglected. N^{14} has three resonance peaks for the (n, p) process between 400 Kev and 1.6 Mev, and the average cross section for that reaction in this region is about 0.02b. The total cross section here is 2b. To slow down a 2 Mev neutron to 400 Kev by elastic collisions requires about 11 collisions, so that only about 10 per cent of the fast neutrons emitted by an atomic weapon will be absorbed by the (n, p) reaction in the atmosphere before they are slowed down. A neutron emitted from a weapon at 2 Mev would travel on an average about 2,300 ft. before being slowed down below 400 Kev. A 400 Kev neutron would be slowed down to near thermal velocities in about 1,700 ft. At thermal velocities N^{14} has a large cross section (1.8b) for (n, p); the (n, γ) cross section is 0.1b, so that approximately 5 per cent of the slow neutrons captured in N^{14} give rise to capture gamma-radiation. The spectrum of this radiation has been measured by Kinsey et al (Reference (2)); it includes strong components at about 11 and 5.5 Mev. The mean free paths of these gamma-rays in air are about 1,300 ft. and 1,000 ft. respectively. Siddons (Reference (3)), has calculated that the gamma-radiation from the (n, γ) process in N^{14} (in the atmosphere and in the high explosive contained in the weapon) probably accounts for about 20 per cent of the gamma-radiation at 3,000 ft. from a nominal weapon of low neutron output type. The (n, p) reactions in atmospheric N^{14} will reduce thermal neutrons to about 1 per cent in 1,000 ft.

The oxygen in the atmosphere plays a negligible part in capturing neutrons, although it helps in slowing them down.

(ii) Water - The hydrogen in water is very efficient in slowing down neutrons. A shield approximately 1 ft. thick would slow down to thermal velocities over 90 per cent of neutrons incident at 2 Mev, and so it may be assumed that such a shield would thermalise most of the neutrons from an atomic bomb incident upon it at any distance of interest.

Thermal neutrons are absorbed in hydrogen by radiative capture (cross section 0.33b), the capture radiation being a single line at 2.2 Mev. This is a much smaller amount of energy than is usually released in a (n, γ) process; the gamma-radiation normally released is of the order of 6 to 10 Mev. According to Cave (Reference (4)) the LD-50 of slow neutrons is about three times that of 2.2 Mev gamma quanta; therefore as these gamma-rays would be very little absorbed in water, a water shield - although decreasing the hazard from fast neutrons - would increase it from slow neutrons. The gamma hazard may be reduced by about 50 per cent by using a saturated solution of borax instead of water. Boron has a large cross section (750 b) for the (n, α) process with thermal neutrons, so that a large fraction of the neutrons are absorbed by this process, although the solubility of borax is only about 2 per cent at normal temperatures. The cost of borax in a saturated solution would be about 1d. per gallon.

In general, it will in any case be necessary to provide a gamma-ray shield against primary radiation from the weapon. If, in these circumstances,

the fast neutron flux is considered to be an additional hazard it may be screened off by a water shield outside the "gamma shelter". The water shield need not be very strong mechanically as most of the neutrons arrive before the shock wave.

(iii) Iron - The total cross section for iron has many resonance peaks in the range 2 Mev to 1 Kev. This suggests that inelastic scattering occurs. The average value of σ_t in this range is 3b. If the scattering were entirely elastic about 30 inches of steel would be required to slow down neutrons from 2 Mev to 1 Kev. As some of the scattering is probably inelastic, the actual thickness required will be less than 30 inches, although it will still be much greater than the 3-4 inch iron shields likely to be encountered in practice. The variation of σ_t with energy below 1 Kev indicates that most of the scattering is elastic and that about 12 inches of steel would be needed to slow down the 1 Kev neutrons to thermal energies.

At thermal energies the cross section for the (n, γ) process is 2.6b and the scattering cross section is 10b, so that most of the thermal neutrons incident on a sheet of steel more than three inches thick would be captured. The capture spectrum can be represented adequately as 1 gamma quantum at 8 Mev plus 0.7 gamma quantum at 5 Mev, for each neutron captured. The LD-50 of gamma radiation of approximately this energy is 2×10^{11} quanta/cm^2; therefore a flux of about 10^{11} thermal neutrons/cm^2 (which is less than 1/10 the LD-50) will give a LD-50 of gamma rays if captured in iron without gamma-ray attenuation. The mean free path of such gamma-rays in iron is 4.2 cm, and thus the self-absorption in a 3-inch shield would reduce the gamma-ray dose by about 50 per cent. Another factor of 2 is gained if the neutrons are incident on only one face of the iron shield (assumed to be an extended plane) since the gamma-rays are emitted isotropically. Even so, it seems that the type of iron shield likely to be encountered offers very little protection against fast neutrons and increases the hazard from slow neutrons.

(iv) Concrete - A concrete containing gravel (mostly silica) as the aggregate, and mixed according to the common recipe (1 part cement, 2 parts sand, 4 parts aggregate, water to cement ratio 0.5, all ratios by volume) will have a density of about 2.3 gm/cc and will contain the following numbers of atoms of the constituent elements per cc:

H	O	Si	Ca	
1.5×10^{22}	4.6×10^{22}	1.8×10^{22}	0.25×10^{22}	atoms/cc

If all collisions were elastic then 1 cm of concrete would be equivalent to about 0.4 cm of water for slowing down neutrons. This would indicate that a concrete shield about 2 ft. 6 ins. thick would be required to thermalise the neutrons from a nuclear weapon. Since there are probably some inelastic collisions with silicon the actual shield required may be less than this.

About 70 per cent of the thermal neutrons absorbed in concrete are captured by the (n, γ) process. With H^1, one 2.2 Mev gamma quantum is emitted for each neutron captured; the remainder are absorbed in the Si and Ca, emitting on the average two 4.0 Mev quanta. Hence the absorption of 3.5×10^{11} thermal neutrons in concrete would result in a LD-50 of gamma-radiation if the gamma-rays were not absorbed. The mean free path of the capture gamma-rays is about five inches in concrete so that the hazard from gamma-rays emitted from a concrete shield thicker than about 12 inches would be less than that from the thermal neutrons incident upon it.

The efficiency of concrete as a neutron absorber can be increased by increasing its hydrogen content, but unfortunately there are not many hydrogen compounds available which would be suitable for use as part of the aggregate. Gugelot and White (Reference (5)), found that the shielding properties could be improved by including limonite ore ($2Fe_2O_3\ 3H_2O$) in the aggregate. They were studying the absorption of neutrons produced by bombarding a beryllium target with 16 Mev protons; such neutrons have a higher effective energy than those from a nuclear weapon, but the results may be used as a guide. Various other improved mixes were tried and it was found that when mixing and transport costs were taken into account, a given attenuation could be obtained more cheaply by using a shield of standard concrete than with a thinner shield of improved concrete. These special mixes are only attractive when space or weight are at a premium.

References

(1) The Effects of Nuclear Weapons, U.S.A.E.C. 1957, p.367.

(2) B. B. Kinsey et al, Canadian Journal of Physics, Vol. 29, p.1 (1951)

(3) A.W.R.E. Report No. E5/54 - "Gamma Emission Resulting from the Radiative Capture of Neutrons by Nitrogen during an Atomic Explosion". (Secret/Atomic/U.K.Eyes Only).

(4) L. Cave, British Journal of Radiology, Vol. 27, p.273 (1954)

(5) P. C. Gugelot and M. G. White, Journal of Applied Physics, Vol. 21, p.369 (1950).

5.2.6 Neutron absorption processes

A neutron in a narrow parallel beam of neutrons passing through an absorber may be removed from the beam by elastic scattering or by capture. If σ_t is the cross section (in cm^2) of a nucleus for the removal of a neutron from the beam in any way, and N is the number of nuclei/cm^3, the number of neutrons (I_x) left in the beam after penetrating a distance x cm, is:

$$I_x = I_o e^{-N\sigma_t x} = I_o e^{-\mu_t x} = I_o e^{-\frac{x}{\lambda}} \qquad (5.2.2)$$

where I_o = number of neutrons in the beam at distance x = o

$\mu_t = N\sigma_t$, is the narrow beam absorption coefficient (cm^{-1})

$\lambda = \frac{1}{\mu}$, is the mean free path (cm).

Nuclear radii are of the order of 10^{-13} to 10^{-12} cm, and it is therefore convenient to express σ_t (which geometrically we would expect to be approximately Πr^2) in barns, where 1 barn = 1b = 10^{-24} cm^2.

The situation described above corresponds to narrow beam absorption; in practice we usually have to deal with situations corresponding to broad beam absorption, where neutrons scattered out of the beam but not absorbed, must also be considered. These can be formally allowed for (as in the gamma-ray case) by introducing a build-up factor, B [x, g(E), M] which will be a function of the distance penetrated (x), the energy distribution of the incident neutrons g(E), and the composition of the absorber (M). In view of the complex way in which the probability of neutron absorption processes depend on the energy of the neutron and the nature of the absorber, it is not generally feasible to deduce the build-up factor analytically. Qualitatively it can be seen that shields composed of elements in which elastic and inelastic scattering predominate will have large build-up factors, whereas any other type of interaction will tend to reduce it. In this connection it should be noted that radiative capture, although it reduces the neutron flux, results in gamma-rays which in many cases are more dangerous than the neutrons producing them.

Neutron cross sections do not show a regular variation with neutron energy and atomic number of the target, but some general trends are observable:

(a) The elastic scattering cross section increases with atomic weight (A) approximately as $A^{\frac{2}{3}}$ (as would be expected if nuclear matter had a constant density), and decreases with increasing energy. The importance of this process for shielding purposes is that it results in a slowing down of fast neutrons. For this to occur with a small number of collisions, A should be small (see Equation 5.2.1.).

(b) The cross section for any other process depends on two factors:-

(i) σ_c, the cross section for compound nucleus formation;

(ii) P_i, the probability that the compound nucleus will decay by process i.

Hence σ_i, the cross section for the process i, is $\sigma_i = \sigma_c . P_i$

The variation of σ_c with energy actually shows many resonance peaks, but if the resonances are averaged out its behaviour at energies less than 0.5 Mev is described fairly well by the relation:

$$\sigma_c \approx \frac{0.5}{E^{\frac{1}{2}}} \text{ barns (E in Mev)} \qquad (5.2.3)$$

For higher energies it is necessary to add to this simple equation a term varying with the atomic weight of the target nucleus as $A^{2/3}$. The equation shows that the capture cross section increases with decreasing energy, which explains why fast neutrons must generally be slowed down in a shield before they can be efficiently captured.

The relative probabilities of the various modes of decay of the compound nucleus are governed by characteristics of the nuclei close to it in mass number. They do not show any regularities, except that at low energies the only possible mode of decay is usually gamma emission.

Most of the information available on neutron cross sections is collected in Reference (1), in the form of a table of thermal neutron cross sections and graphs of σ as a function of energy for each isotope investigated. Reference (2) gives a summary of information on fission neutron reaction cross sections.

References

(1) Hughes and Harvey, Neutron Cross-Sections, USAEC Report BNL-325 (1955)

(2) Nucleonics Vol. 13 (No. 11) p.67, Data Sheet No. 8.
Neutron Physics, Fission Neutron Reaction Cross Sections.

5.2.4 Lethal dose of neutrons

The lethality of any radiation is described in terms of the dose which would be responsible for the death of 50 per cent of the exposed population. This dose is referred to as the 50 per cent lethal dose, or LD-50.

The LD-50 of neutrons for man depends on the energy of the neutrons, but there is some doubt as to the extent of this dependence. In Reference (1) it is stated that the generally accepted values of the lethal doses of slow (less than 0.2 ev) and fast (greater than 3 Mev) neutrons are 5×10^{11} neutrons/cm^2 and 10^{11} neutrons/cm^2 respectively. Marley (Reference (2)) takes 4×10^{11} neutrons/cm^2 and 10^{10} neutrons/cm^2 as the LD-50s for these two groups. Cave (Reference (3)), assuming that the lethal dose creates in the body an amount of ionisation biologically equivalent to that created by the lethal dose of gamma radiation (400r), arrives at the dependence of lethal dose on energy shown in column 2 of Table 1. Account is taken, both of the high energy protons from neutron collisions, and of the capture gammas. These values are based on a relative biological efficiency (r.b.e.) for fast protons of 6.5, i.e. it is considered that a given amount of energy released in tissue by fast protons is biologically equivalent to 6.5 times that amount of energy released by gamma-rays. It is now thought that this is too high for acute exposures and values between ~~1.7~~ 1.4 (Reference (4)) and 0.5 (Reference (5)) have been suggested for this case. Column 3 of Table 1 results from Cave's data when 1.3 is taken as the r.b.e. of fast protons.

TABLE 1

Relation between Neutron Energy and Lethal Dose

Neutron Energy	LD-50 (Neutrons/cm^2) (Proton r.b.e. = 6.5)	LD-50 (Neutrons/cm^2) (Proton r.b.e. = 1.3)
Thermal	1.6×10^{12}	1.6×10^{12}
1 Kev	1.8×10^{12}	1.8×10^{12}
3 Kev	1.7×10^{12}	1.8×10^{12}
10 Kev	1.4×10^{12}	1.6×10^{12}
30 Kev	9.2×10^{11}	1.5×10^{12}
100 Kev	4.1×10^{11}	1.1×10^{12}
300 Kev	1.6×10^{11}	5.9×10^{11}
1.0 Mev	5.0×10^{10}	2.2×10^{11}
3.0 Mev	1.6×10^{10}	8.2×10^{10}

References

(1) The Effects of Atomic Weapons, U.S.A.E.C., 1950

(2) A.E.R.E. Report No. HP/R.422

(3) L. Cave, British Journal of Radiology, Vol. 27, page 273 (1954)

(4) The Effects of Nuclear Weapons P.363, U.S.A.E.C., 1957

(5) Radiological Hazard Evaluation, U.S.N.R.D.L., 1957.

5.2.3 Angular Distribution at the Target

Very few measurements of the angular distribution of neutrons at the target have been reported. Western (Reference (1)) found that a thick wall 18 feet long by $7\frac{1}{2}$ feet high reduced the fast neutron flux to between 13% and 23%, showing that at least this part of the flux is due to scattered neutrons.

It is generally considered (e.g. see Reference (2)) that the distribution of slow neutrons is isotropic at distances from the detonation greater than 1,000 feet, as such neutrons have been scattered many times. The fast neutron angular distribution will, however, show a tendency for neutrons in this group to be incident from the direction of the explosion.

The angular distribution of neutrons at the target is considered by Mehl in Reference (3). At 900 metres from a nuclear test explosion less than one per cent of the flux in the energy interval between 0.7 and 1.5 Mev was from unscattered neutrons, yet the distribution was peaked quite strongly in the outward direction. As the neutrons were moderated to lower energies the distribution became more nearly isotropic, but it still peaked outwards. Preliminary results from this test are given in Table I.

TABLE 1

Angular Distribution of Neutron Flux at 900m from Weapon

θ°	Neutron Energy Band		
	200 eV/0.1 Mev	0.1/0.7 Mev	0.7/1.5 Mev
90° - 60°	0.85	0.38	0.18
60° - 30°	0.75	0.30	0.07
30° - -10°	0.60	0.20	0.03
-10° - 660°	0.52	0.16	0.02
-60° - -90°	0.45	0.14	0.015

θ = Angle from vertical in plane including the weapon, measured positive on side away from the weapon.

References

(1) Attenuation and Scattering of Initial Nuclear Radiation, Home Office Report CD/SA.85. (Confidential)

(2) The Effects of Nuclear Weapons, page 368, U.S.A.E.C., 1957.

(3) Scaling Neutron Flux with Altitude, C.R. Mehl. Tripartite Conference on Effects of Atomic Weapons (1957).

5.2.5 Lethal range of neutrons

The lethal range of neutrons is the distance at which the neutron dose has fallen to the LD-50. It can be assessed, for unshielded persons, from the neutron dose/distance relationship (Figures 8 and 9 of Sections 3.1, Chapter 3), if the power of the weapon and its relative neutron yield are known. Alternatively it can be deduced from the neutron flux/distance relationship if the value of the r.b.e. appropriate to the fast protons produced in tissue is also known.

Table 1 gives the lethal ranges obtained from these curves in conjunction with Table 1 of Section 5.2.4, for a number of yields. It also gives the lethal range of the gamma radiation for comparison. The Table shows that where neutron flux measurements only are available for a weapon the lethal range can be estimated from these measurements assuming a proton r.b.e. value of 1.3. It will be seen that even for high neutron yield weapons the gamma radiation lethal range is greater than that of the neutrons for yields in excess of about 20 KT.

TABLE 1

Lethal Ranges for Neutron and Gamma Radiation (Feet)

Weapon Yield KT	Low Neutron yield weapons			High neutron yield weapons			Gamma Rays
	Dose Data	Flux Data		Dose Data	Flux Data		
		Proton r.b.e.			Proton r.b.e.		
		1.3	6.5		1.3	6.5	
1.0	1230	1290	1710	2460	2400	2970	2070
10	2100	2130	2670	3600	3480	4140	3390
100	3150	3150	3750	4830	4680	5430	5280
1000	4290	4290	5040	6210	6000	6750	7950

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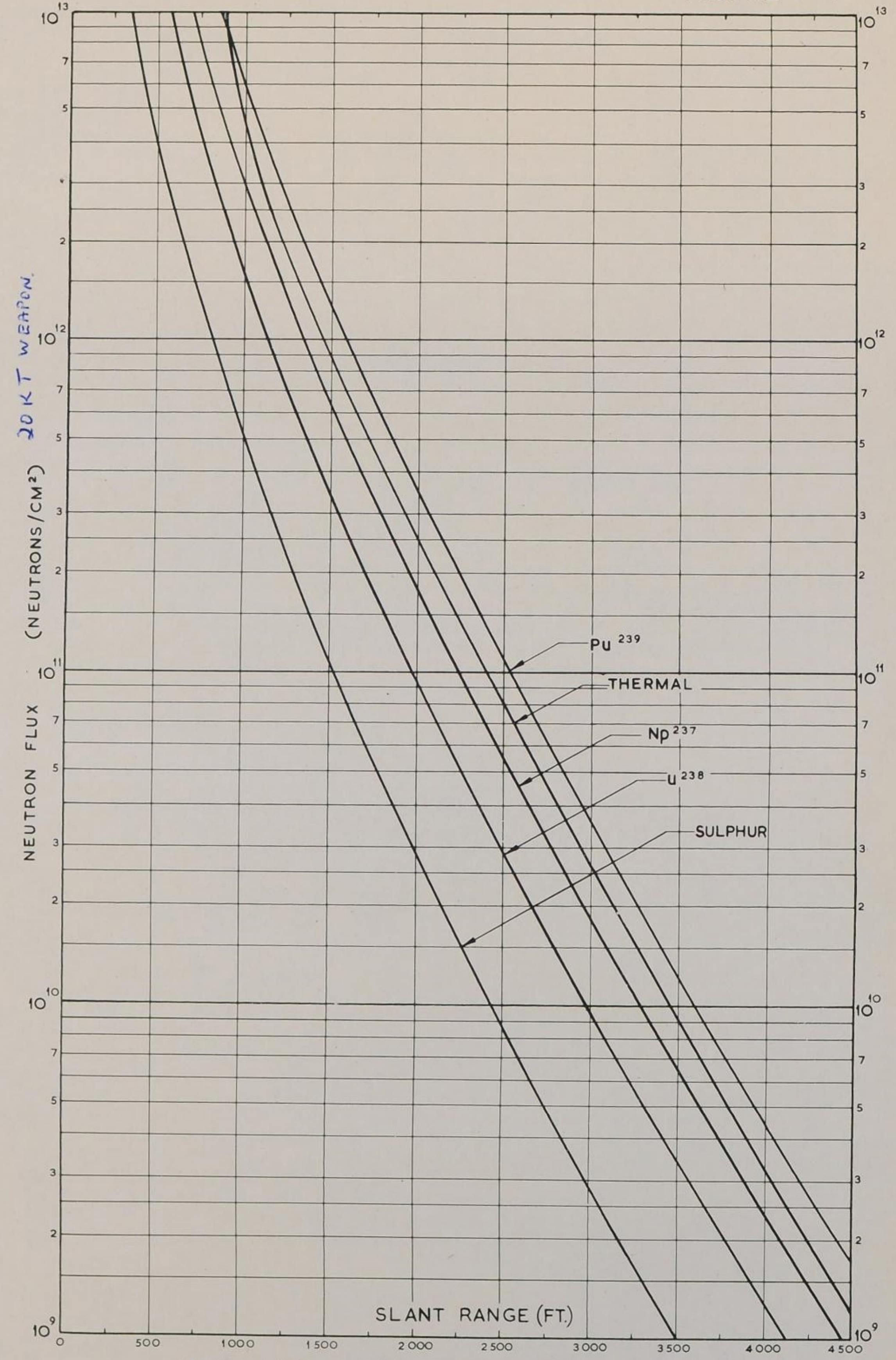
PART VII
CHAPTER 5
SECTION 5.2.2
FIGURE 1



FAST AND THERMAL NEUTRON FLUXES
AS A FUNCTION OF SLANT RANGE

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CHAPTER 8 - DECONTAMINATION

8.1 General Considerations

8.1.1 The nature of the problem

The radioactive contamination produced by the explosion of a nuclear weapon cannot be destroyed, since radioactivity is a property of the atomic nucleus. The hazard associated with this contamination may be dealt with in three ways. Firstly, by disposing of the whole of the contaminated material by deep burial in the ground or at sea; secondly, by keeping it at a safe distance until the radioactivity has decayed to a tolerable level; and thirdly, by removing the contamination from the material. The third method (i.e. decontamination) therefore consists of removing the contamination from surfaces where it is dangerous and disposing of it where it can do no harm.

The method adopted in any particular case will depend on a number of factors. These include, with reference to a specific contaminated object or area, the initial and maximum tolerable intensities of the radiation, decay rate, cost or disposal and replacement, strategic value, and the work to be done in decontamination. Large structures could not easily be disposed of, but decontamination could be undertaken after the activity had decayed sufficiently to permit the work. In the case of smaller objects having high activity, burial might be more economical. In many instances it might be an advantage merely to isolate the object or structure and allow the activity to decay. Beta and gamma radiation emitted by contamination arising from a fission explosion will decay approximately in accordance with the equation:-

$$I_t = I_o.t^{-1.2} \tag{8.1}$$

where I_o and I_t are the radiation intensities at unit time and after time t respectively.

In Reference (1), which records observations made at Operation Mosiac, it is noted that the decay of residual gamma activity corresponded to a slope of $t^{-1.7}$. A report by Dunning (Reference (2)) on observations made in the Marshall Islands following a U.S. nuclear test, notes that during the first ten days after detonation the decrease in activity corresponded to a slope of $t^{-1.2}$. From 25 days up to 1 year the slope was approximately $t^{-1.7}$.

References

(1) A.W.R.E. Report No. T.21/57

(2) G. M. Dunning "Criteria for Evaluating Gamma Radiation Exposures from Fallout following Nuclear Detonations". Radiology, Vol. 66, No. 4, pp.585-94, April, 1956.

8.1.2 Origins of Contamination

Radioactive contamination may be caused by the fission and other active products from a nuclear explosion (reference Chapter 7), by neutron-induced activity in soil and water (reference Chapter 3.2), and from any fissile material remaining after the explosion.

The fission products will be responsible for the emission of beta and gamma radiation, and the unused fissile material for the production of alpha rays. Owing to the long half-life of the fissile material and its dispersion by the explosion, the resultant alpha radiation will usually be negligible, although in the case of a very inefficient explosion (a 'fizzle'), an appreciable quantity of fissile material will be distributed over a limited area, with consequent increased danger from alpha radiation.

Contamination from fission products and fissile material will be confined to surfaces, whereas neutron-induced activity may be produced at depths as great as several feet below surfaces. Some of the more important radio-isotopes produced in this way are listed in Table 1. Further details of neutron-induced activity may be obtained from References (1) and (2).

Table 1 - Neutron Induced Radio-Elements

Element	Radio-Element	Half-life of Radio-element	Types of Radiation
Aluminium	Al 28	2.3 min.	β, γ
Chlorine	Cl 38	37 min.	β, γ
Copper	Cu 64	12.8 hr.	β, β^+, γ
Iron	Fe 59	45 days	β, γ
Magnesium	Mg 27	9.6 min.	β, γ
Manganese	Mn 56	2.6 hr.	β, γ
Nitrogen	C 14	5,600 years	β
Sodium	Na 24	15 hr.	β, γ
Zinc	Zn 65	245 days	$\beta+$, γ

These induced radio-isotopes will be present in depth and decontamination will not be possible. However, owing to the limited range of the neutrons (reference Chapter 3.2) this form of activation will seldom extend to material which was more than a few hundred yards from the point of the explosion at the instant of burst.

References

(1) D.A.W.Plans Note No.15 - Neutron-Induced Radioactivity

(2) A.W.R.E. Report T35/58.

8.1.3. Effect of type of burst and terrain

In the case of low overland and air bursts the fission products and unused fissile material appear in the form of oxides and ntirides, most of which are carried up with the cloud of debris. The local fallout from such explosions is a dry, inert dust highly resistant to chemical treatment. On the other hand, an underwater explosion produces a chemically reactive form of fission product which may be present in droplets of mist or as an aqueous mud slurry. These two types of contamination - 'reactive' and 'inert' - are likely to respond differently in decontamination operations, but in many cases however, the fallout will be of an intermediate type. For example, an air burst on a cloudy or rainy day may produce more reactive contamination than on a clear bright day. The nature of the contamination likely to arise from various types of burst is summarised in Table 1, which is taken from Reference (1). The advent of dew or rain is likely to blur these distinctions.

TABLE 1

Contamination Resulting from Various Types of Burst

Type of Burst	Degree of Contamination	Reactivity
High Air	Slight	Inert
Low Overland	Moderate	Inert
Low Overwater	Moderate to heavy	Fairly reactive
Underwater	Heavy (base surge cloud)	Reactive
Underground	Probably heavy to very heavy	Mainly inert
Rain precipitated contamination	Variable	Mainly reactive

The removal of reactive contamination may be assisted by chemical means if the chemical nature of the contaminant is known. The percentages of various elements in a fission product mixture are continuously changing, but the basic alkaline earths, rare earths, and other metallic elements, predominate. Two exceptions are iodine and tellurium, which are acidic in character. The chemical nature of the elements contained in inert contamination, which settles as dust, is not important in decontamination operations in the field.

References

(1) A.W.R.E. Report No. 0-49/55 - %A Guide to Radiological Decontamination after a Nuclear Explosion or Radiological Attack". (Official Use Only)

8.2. The Effect of Surface Conditions

The fallout from a nuclear explosion will settle in the form of particles of various sizes (reference Chapter 7), and the coarser particles will simply lie on the surfaces on which they come to rest, being removable by sweeping or suction. Finer dust particles may be attached to the surface by various means, such as adhesion by grease, or trapping by the pores in a rough surface.

Attachment by a form of ion-exchange is likely in all cases where the contaminant is soluble and may also occur in the case of surfaces which have available acid groups. These groups would be provided by organic surfaces such as paint, plastics and textiles, and also by glass. Ion-exchange between the acid groups and basic materials present in soluble or reactive contamination gives rise to strong adhesive forces. Chemical exchange may also occur on metal surfaces.

The results of tests to examine the influence of surface roughness, hardness and cleanliness on the contamination - decontamination behaviour of various materials (e.g. glass, tiles, metals, plastics, paints, etc.) have been reported in Reference (1).

The tests involved both a surface and underground burst, and the conclusions reached may be summarised as follows:-

(i) Surface roughness had no clearly defined effect on contaminability. Surface roughness did affect decontaminability by factors of 6-10 (for residual activity), the rough surfaces retaining more contamination than the smooth.

(ii) From data obtained with polyisobutylene it appeared that soft surfaces were contaminated to a greater degree than hard surfaces, and retained two to three times more activity (absolute) after decontamination, than hard surfaces.

(iii) Artificially soiled surfaces were more easily contaminated than clean surfaces by a factor of 2 to 7.5, but were decontaminated as well as, or better than clean surfaces.

(iv) Navy grey paint was from 1.5 to 12 times as contaminable as bare aluminium, glass, and chromium-nickel steel, but all these materials were readily decontaminated.

Results from further tests reported in Reference (1) show that contamination on horizontal surfaces was greater than on non-horizontal surfaces by factors up to 30 to 40. Vertical surfaces retained smaller particle sizes than inclined or horizontal surfaces. Very extensive measurements are reported in detail, and include a wide variety of surfaces and treatments.

References

(1) U.S. Armed Forces Special Weapons Project Report No. WT-400 "Operation Jangle".

Project 6.2 "Protection and Decontamination of Land Targets and Vehicles". (Secret)

8.3. General Decontamination Methods

8.3.1. Introduction

The method selected for decontamination will depend on the type of contamination, the extent of removal desired, the nature of the surface and the size of the object.

The methods available for the decontamination of objects, structures, roads, etc., may be considered under four headings:-

(i) Sweeping and vacuum cleaning.

(ii) Detergency

(iii) Chemical treatment

(iv) Surface removal.

In the case of land reclamation, special techniques requiring earth-moving equipment may be employed.

In all of these methods the techniques must be arranged to give the maximum possible protection to the operators, who will require adequate protective clothing, and suitable instruments for the measurement of radiation levels.

Since the object of decontamination work is to remove and confine the activity, an essential consideration is the disposal of contaminated waste. This must be conveyed or otherwise removed to a location where it does not constitute a danger.

8.3.2. Sweeping and vacuum cleaning

These are dry methods and in general tend to be more hazardous than wet processes. They are of use however, where the contaminant is mainly of an inert dusty nature. Vacuum cleaning is safer and more efficient than brushing, but the filters in commercial equipment do not ensure complete retention of radioactive dust.

A comparison between vacuum technique and high pressure hosing is given in Reference (1), and states that decontamination by vacuuming is relatively inefficient. Vacuuming at a decontamination rate of 40 sq.ft. per equipment-hour left a high residual contamination ranging from 9 to 84%. A high pressure water stream with detergent additive, on the other hand, cleaned a rough roof surface, slag or gravel finished, at a rate of approximately 600 sq.ft. per equipment-hour and left an average residual contamination of less than 2%.

It should be noted however that much will depend on the precise conditions, particularly particle size of the dust, and in many cases vacuum cleaning can be very efficient.

8.3.3. Detergency

This method consists of wet treatment of the surface with a detergent solution and is a relatively cheap and safe process. It is particularly effective in cleaning inert dusty contamination from smooth surfaces, but is less useful on surfaces where adsorption has occurred. Reactive contamination will respond to the use of a suitable detergent, and the nature of the detergent is of greater importance in this case.

The hazards from ingestion and inhalation of loose dust from a surface are considerably reduced by washing or spraying down the surface with detergent solution. In cases of more persistent contamination scrubbing or brushing will give improved results. The composition and application of various detergent solutions are given in Section 8.8, and the techniques for their use in Section 8.9.

8.3.4. Chemical treatment (complexing)

This treatment is carried out as a wet process using a solution of a "complexing" agent in conjunction with detergent action. The method is particularly suitable for removing reactive contamination from textiles, from smooth or thin porous surfaces, and from surfaces in general which do not respond satisfactorily to straight detergent. The complexing agent is a normally non-corrosive substance which will convert the contamination into a chemical form which is no longer retained by the surface. An example of such a substance is ethylene-diamine-tetra-acetic acid (EDTA). Details of this method and its application may be obtained from References (2) and (3).

8.3.5. Surface removal

This method may be carried out by a large variety of techniques, most of which are laborious but eventually very effective. Complete decontamination is usually possible.

Abrasive compositions are best applied under wet conditions together with the detergent and other additives. The composition of an efficient scouring paste is given in Section 8.8. Suitable chemical agents may be selected for specific types of surface, for example, acids for metal cleaning, and alkaline solution or suitable solvents for paint stripping.

Flame decontamination may also be considered as a surface removal technique. Reference (1) gives a description of a flame decontaminating unit (USNRDL Flaminator) incorporating a burner, a surface removal tool, and a vacuum pick-up system, which was tested on wood, asphalt and concrete surfaces contaminated by an underground burst atomic weapon. No apparent hazard is involved in the maintenance of the Flaminator, but during operations the operator must be protected by an efficient respirator.

8.3.6. Land reclamation

Since the contamination is mainly held in the superficial layer of soil, the radiation field from a contaminated natural land area may be reduced for limited sectors by standard methods of earth movement such as ploughing, harrowing, scraping and filling. The use of such surface techniques is described in Reference (1). It is stated that time, man-power and equipment requirements do not differ significantly from those that would apply in the absence of radioactive contamination. Tests were made following a surface burst, and the test area was plane and free from gulleys and surface irregularities, and covered to about 10% by sage brush from one to three feet high. The soil was a non-compacted, non-cohesive silty sand weighing about 150 lb./cu.ft. The moisture content, owing to rainfall before the weapon burst, was about 20% to a depth of 6 inches. It is stated that the radiation fields were reduced 70 - 90% through the use of standard earth-moving procedures and equipment. In the scraping operations, it is unnecessary to haul the spoil any further than the boundaries of the area to be treated, and this material should be spread in a layer two to four inches deep.

Owing to the shielding afforded by the equipment the operators receive from 60 - 70% less readiation dosage than unshielded personnel working in the same area at the same time. Internal hazards due to the presence of airborne activity during operations can be minimised by the use of standard protective clothing and full-face respirator. Contamination of operating equipment does not constitute a serious hazard. In general, equipment will pick up a maximum of 10% of the level of the field in which it operates. Decontamination to acceptable tolerance levels can be accomplished adequately with high pressure hoses.

Another method also described in Reference (1) is designed to give protection to personnel traversing or occupying a radioactively contaminated region, by interposing earth barriers between the radiation source and the area occupied. It was found that an earth wall 4.5 ft. high, on each side of a 30 ft. wide roadway, reduced the radiation field in the roadway by a factor of about 3.5.

The radiation intensity at the bottom of a fox hole and a trench was found to be less than that at 3 ft. above the ground by a factor of about 20.

A circular cleared area 180 ft. in diameter afforded a radiation reduction of a factor of 5, measured 3 ft. above the centre. It was determined that increases in the diameter of the clearing beyond 200 ft. did not afford any significantly greater reduction at the centre.

In comparing barrier and surface techniques, it was found that for a given amount of time, and using identical equipment, surface clearing yielded a greater maximum reduction in the radiation field (by a factor of 1.5) and produced approximately four times the working area produced by the barrier technique.

The recontamination of treated areas through wind action is relatively unpredictable on the basis of present knowledge.

References

(1) U.S. Armed Forces Special Weapons Project, Report No. WT-400, Operation 'Jangle'. Project 6.2 "Protection and Decontamination of Land Targets and Vehicles. (Secret)

(2) A.W.R.E. Report No. T22/57, Operation Buffalo, Decontamination Group Report, Parts 1-4. (Confidential)

(3) A.W.R.E. Report No. T63/57. The Handling, Servicing and Decontamination of Radioactive Aircraft. (Official Use Only)

8.4 Decontamination of Vehicles and Aircraft

Vehicles. Information regarding the contamination and decontamination of military vehicles at an atomic weapon test has been obtained from Reference (1). No difficult problems of decontamination were experienced, although vehicles operated in areas contaminated at levels up to 50r/hour, and included Weasels which operated on the lip of a surface burst crater $2\frac{1}{2}$ hours after the time of burst. These Weasels were monitored approximately 24 hours after the burst time and had a general level of contamination of 30 mr/hour. Their treads gave readings of 70 mr/hour, and the levels of activity in the personnel compartments were 10 mr/hour.

Tanks which were operated in the same areas one day after the surface explosion displayed activity levels two or three times background.

High levels of intensity (up to 13r/hour) were noted in the beds of vehicles used for transporting contaminated material from radioactive areas.

Soil properties influenced the degree of contamination, and it is believed that fine dry soil of the type present in the test area lessened the decontamination problem. Under wet conditions greater contamination of the vehicle occurs, although the dust hazard to the operators and the upper surface contamination of the vehicle is reduced.

It is recommended that vehicle decontamination procedures be based on the urgency of the situation and that the following emergency methods may be used by the vehicle operator.

(i) Dry sweeping or brushing of the vehicle, paying particular attention to the removal of as much dirt as possible from the cab.

(ii) Wiping with wet rags.

(iii) Brush scrubbing with water, or soap and water; if plentiful water is available more thorough decontamination could be achieved by hosing down with water and scrubbing.

(iv) Greasy or oily areas may be cleaned by petrol applied on brushes or rags, (water is ineffective in this case).

A detailed account of the decontamination of vehicles (3-ton trucks, 1-ton trucks, Landrovers, armoured scout cars, etc.) used at Operation Buffalo is given in Reference (2). Steam cleaning was found to be the quickest and most satisfactory method for extensive and greasy areas, e.g. engines, chassis and vehicle surfaces generally. A disadvantage in the use of steam was the lack of both control and visibility. High pressure hosing was a little slower, but more economical.

Aircraft. The decontamination of aircraft used at two British trials is reported in Reference (3) (Operation Mosaic) and Reference (2), (Operation Buffalo). It is noted in the latter reference that the contaminant, in contrast to ground fallout, appeared to be largely ionic and therefore required the use of complexing agents or barrier films for efficient removal. The initial levels were relatively uniform, suggesting absorption contamination mechanism rather than impaction. Reference (2) gives much detailed information on decontamination materials, procedures and man-power requirements for both vehicles and aircraft. A manual dealing exclusively with the handling, servicing and decontamination of radioactive aircraft

has been prepared (Reference (4)).

The effectiveness of various methods and cleaning compounds for the decontamination of aircraft contaminated by flying through an atomic cloud were investigated during the U.S. Operation Snapper, and are reported in Reference (5). Methods using brushing techniques were generally more effective than those not involving brushes. A solvent emulsion grease cleaning compound ("gunk" USAF Spec. 20015) was one of the most effective cleaning agents. Tests were made to determine the influence of surface condition, i.e. oiled, cleaned and polished, on contaminability. Surfaces coated with a light film of oil contaminated to a level six times as high as a clean clad aluminium surface. Polished surfaces became only half as contaminated as the clean clad aluminium.

Ultra-violet light and fluorescent zinc sulphide were employed to determine the possible contamination distribution throughout the interior of jet aircraft. Stepwise decontamination showed that the cockpit dose-rate could be reduced by approximately 60 per cent by decontaminating the air intake duct, tail pipe, and exterior surfaces. The remaining 40 per cent was contributed by the engine, residual contamination and contaminated places not accessible for decontamination. It should be noted however, that the effect of various measures on cockpit dose-rate will vary with the particular aircraft, and especially with the distance between the engines and the cockpit. Further, the validity of using zinc sulphide as a simulant is not established.

Regarding aircraft in general, a distinction should be made between aircraft contaminated on the ground and those contaminated in the air. Barrier films are effective in countering airborne contamination, by preventing contact between the soluble contaminant and the paint surface, (see References (2) and (4) for details).

References

(1) U.S. Armed Forces Special Weapons Project, Report No. WT-400, Operation Jangle. Project 6.2 - "Protection and Decontamination of Land Targets and Vehicles". (Secret)

(2) A.W.R.E. Report No. T22/57. Operation Buffalo, Decontamination Group Reports, Parts 1-4. (Confidential)

(3) A.W.R.E. Report No. T33/57. Operation Mosaic, Aircraft Decontamination (Confidential)

(4) A.W.R.E. Report No. T63/57. The Handling, Servicing, and Decontamination of Radioactive Aircraft. (Official Use Only)

(5) U.S. Armed Forces Special Weapons Project, Report WT-535 (March, 1953) Operation Snapper, Project 6.5 "Decontamination of Aircraft". (Confidential/Atomic)

8.5. Decontamination of Food and Water

Food protected by cans, dust-proof wrappings, or other effective measures should undergo little or no contamination from fallout. There is no practical means of salvaging food which has become radioactively contaminated.

Water supplies might be contaminated by radioactive dust falling on a reservoir or other source of supply. In surface waters the radioactive contaminants will tend to be adsorbed by suspended and colloidal matter and will eventually settle or be deposited on any available surface. Material carried out from a reservoir is likely to be removed by the normal water purification process, which usually includes sedimentation and filtration stages. Because of the absorptive properties of soil, underground sources of water such as springs and wells would usually be safe from contamination.

If a river or reservoir is seriously contaminated, and the water is not subjected to any purification processes, the water may be unfit for consumption for several days. Careful examination of the supply would be necessary, and it must be remembered that in this connection alpha and beta activity, as well as gamma, are very important.

Contaminated water may be purified by the use of cationic and anionic exchange columns (de-mineralisers) and also by distillation. The mere boiling of water contaminated with radioactivity is of no value. The accepted safe tolerance level for water containing fission products is 4×10^{-6} microcuries/cc. Acceptable emergency activities for drinking water are given in Table 2, Section 3.3 of Chapter 3.

A method of removing dissolved fission products from potential drinking water supplies in the field has been developed at the Water Pollution Research Laboratory (DSIR). Reference (1) deals with field trials of a 1/20 scale apparatus that was used at Operation Buffalo. The apparatus worked effectively, with the exception of the removal of radioactive iodine.

Factors affecting the usability of contaminated foodstuffs are discussed in Reference (2), of which further details are given in Chapter 3, Section 3.3.

References

(1) A.W.R.E. Report No. T4/57 (Confidential) - "The Decontamination of radioactively contaminated drinking water in the field".

(2) A.W.R.E. Report No. 0-34/56 (Official use only) - "Ingestion of Food Contaminated by Atomic Explosions".

8.6. Protective Measures

The best protection against radioactive contamination is to use surfaces which are resistant to such contamination or from which the activity may be easily removed. Large-scale measures of this kind would hardly be feasible, but some action could be taken where there is a high probability of contamination, and anti-contamination measures are desirable.

Certain materials, such as polythene, P.V.C. and paper of suitable strength, may be used for form thin protective surface layers on various articles.

Structural materials such as brick, concrete, and wood are a special problem, since the complete decontamination of porous materials is almost impossible. The best means of protection is a good coating of a sealing agent such as paint. In designing structures, the avoidance of cracks, concavities, inaccessible spaces and poor drainage, would facilitate decontamination operations.

A means of protection which could be used where large quantities of water are available is the pre-wetting of exposed surfaces. For example, by saturating the paintwork on a ship with water, the uptake of reactive contamination from mist or spray is greatly reduced, and the surface may easily be decontaminated by further washing with water.

Barrier paints are particularly suitable for the protection of aircraft surfaces. The requirements for a barrier paint or film include ease of application, ease of removal, durability and weather resistance. The satisfactory use of barrier paints at British Trials is reported in Reference (1).

A further point is that where vehicles and the like are to enter an active area all non-essential accessories should be removed to minimise the work of decontamination. Canvas canopies on trucks are an example.

References

(1) A.W.R.E. Report No. T22/57, Operation Buffalo, Decontamination Group Report, Parts 1-4. (Confidential)

8.7. Waste Disposal

The disposal of contaminated waste is a problem which must be overcome in any decontamination work. The exact method used in any particular case will be determined largely by the circumstances, but ultimately disposal can be achieved only by dilution or storage.

The disadvantage of hosing down (except at sea) is that large volumes of water must be diposed of.

All highly contaminated waste, whether in solid or liquid form, must be collected and stored, or buried at sea or on land. In some cases it is possible to reduce the volume and concentrate the waste by burning, but care must be taken not to release the radioactive dust into the air.

Contaminated water of low activity may be allowed to soak away through the soil, which will absorb much of the activity. In an emergency, the disposal of contaminated water into the sewage system might be permissible.

In the case of burial of solid material (or soak-away of water) the site must be marked so that subsequent accidental exposure to the residual activity may be avoided.

8.8. Recommended Decontamination Agents - Composition and General Application

The agents listed in this section are based on an A.W.R.E. Report (Reference (1)), but have been amended to include some more recent formulations recommended by the author of that report.

A. Detergent

"Fully-built" synthetic detergents are far more effective than the simple "unbuilt" detergents, although the latter are better than nothing.

A suitable formulation for the fully-built type is as follows:-

Alkyl aryl sulphonate (Nervan EL.)	2.5 parts
Sodium Tripolyphosphate	8 parts
EDTA Acid	0.25 parts
Cellofas	0.25 parts
Soda Ash	1 part

This may be used at 0.3% w/w upwards. (5 oz./10 galls. upwards).

Uses - All general work, especially on smooth surfaces.

Hazards - None, c.f. normal domestic detergent.

B. Strong Alkali with Detergent

Any strong alkali may be used; caustic soda is very strong and cheap and is thus very suitable. Use 3 to 16 ozs. per gallon of solution as the severity of treatment demands. $1\frac{1}{2}$ ozs. per 10 gallons addition of a wetting agent or detergent (Lissapol N is suitable) will aid the penetration of this solution.

Uses - Paint stripping etc., quickest when hot. Use at full strength. Degreasing - more dilute solutions may be used, or caustic soda replaced by sodium metasilicate or trisodium phosphate. More efficient when hot. May be used in conjunction with a scouring powder such as pumice. May not be used on aluminium and magnesium alloys.

Containers - Steel buckets, cans and tanks are suitable.

Hazards - Corrosive; must be kept away from skin, tongs and/or rubber gloves should be used.

C. Complexing Detergent Solution

An example of this is SDG3, which comprises:-

EDTA Acid	1 part
Citric Acid	2 parts
Sodium Carbonate	0.6 parts
Water	1 part
Alkyl Sulphate Detergent (20%) solv.	1.5 parts
Sodium Sulphate (anhydrous)	2.5 parts

The normal working strength is 0.8% w/w. The pH valus should be 3-4. A considerable improvement will result from the addition of one part sodium fluoride, but the mexture will then be poisonous.

Far more effective if used hot or with steam.

Uses - The above preparation is more effective if used as a bath treatment or applied as a cream after thickening with 2% w/w sodium alginate (Manutex SA/KP) and left for a short time to act, rather than if used as a straight wash down as a detergent. The solution is suited to all surfaces, especially paint, plastics, non-ferrous metals, glass and textiles.

Containers - Enamel buckets and cans are very suitable, but where these are not available steel or galvanized buckets or tanks may be used, in which case it is preferable that they be given one or two good coats of paint, preferably bitumen paint, on the inside. Stainless steel is the ideal material, brass is a reasonable second best.

D. Laundry Detergent

The solution given under Type A above will prove adequate for the treatment of clothing in commercial laundry machines. Where soft water is available a soap-based detergent liquor is to be preferred, for example:-

	Nominal Washing Strength
EDTA Acid	0.02% w/w
Soda Ash	0.09%
Sodium Tripolyphosphate	0.2%
Cellofas B or D	0.01%
High Titre Soap	0.1%

In severe cases the EDTA and Soda Ash content may be raised to 0.05% and 0.12% respectively. The pH value should be 9.5.

The process may follow the standard pattern, but without any initial breakdown soak. In a two-wash process the first wash may be at 140 - 160°F, the second up to boiling if the goods will allow. The exact quantity of stock solution will vary according to conditions.

Severe contamination of clothing may be removed by an overnight soak in the Complexing Detergent Solution, after the above process.

E. Detergent

This is a special detergent for grease and possesses very good emulsifying powers. The only British detergent of this type is Lissapol N (I.C.I.), (Stergene), and may be used at strengths between 4 and 80 oz. per 10 gallons. In cases where a reactive contamination is present, a complexing agent (Sequestrol M, 8 oz. per 10 gallons) may be added with benefit.

Uses - Degreasing and cleaning of surfaces generally, but particularly where strong alkali, etc., is undesirable.

Hazard - None. Prolonged contact with skin should be avoided.

Note - This detergent is normally cloudy in hot solutions. It rinses off better in cold water.

F. Scouring Powder

Fine pumic powder or any proprietary scourer may be used here. A more satisfactory preparation is made if a detergent and complexing agent are also added. The following is a very satisfactory preparation and is non-drying:-

Scouring paste:	8% SDG3 (vide C)	30 parts dry weight
	300 mesh Pumice Powder	40 parts
	Glycerine	20 parts
	Sodium Alginate (Manutex SA/KP)	1 part

Uses - General cleaning of all non-porous surfaces, especially hard materials. Very useful decontaminant where non-abrasive methods fail.

Hazards - None. Many other abrasive powders, e.g. titanium oxide, felspar, etc., may be used in place of pumice.

G. Acids

A wide range of acids may be used where such are permissible. For ferrous materials standard rust removing acids are satisfactory, e.g. sulphuric acid, at 1-25% strength.

Other good mextures are:-

a - oxalic acid (1% upwards)

b - 6% nitric acid plus 1% sodium fluoride

c - 2% oxalic acid plus 1% sodium fluoride.

Uses - These may be used on almost any surface where fast or highly efficient decontamination is required. Metals will tend to dissolve, and glass will be etched to some extent by the fluoride solutions.

References

(1) A.W.R.E. Report No. 0-49/55 - "A Guide to Radiological Decontamination after a Nuclear Explosion or Radiological Attack". (Official Use Only)

8.9. Recommended decontamination techniques for specific cases.

Surface or Article	Decontaminating Agent	Ref. Sect. 8.8	Type of Contamination and Action	Procedure	Remarks
Asphalt, Bitumen	Water from hoses, with brushing		Very effective for inert dust, less effective for reactive contamination; erosion.	Work from less active to more active areas, and down-hill on sloping surfaces. Brushing may be used with advantage.	Activity will collect in gullies and drain traps. Suitable for large areas. Avoid undue spray.
	Scrubbing with detergent	A	All types of contamination.	As above.	Suitable for smaller areas.
	Strong alkali with detergent	B	Ditto Dissolves surface.	Work in small patches Sluice down with water after treatment.	Suitable for smaller areas.
	Complexing detergent solution.	C	Effective for reactive contamination. Dissolves contamination.	Work in small patches, apply solution, keep wetted with spray if necessary, leave for 30 minutes or longer and finally wash off. Use as hot a solution as possible.	Applicable to small special areas. Solution is relatively expensive.
Brick Concrete	Vacuum cleaning (preferably with brush)		Suitable for dry dust contamination on rough surfaces.	Usual technique, work downwards.	Special machines are preferred. Machine becomes contaminated. Means of safe disposal of effluent air are required (special filters). (Respirators may otherwise be required).
	Hosing down and brushing		Suitable for inert dust, and on relatively smooth surfaces.	As for Asphalt	Wetting is likely to fix reactive contamination in the surface layers.
	Flame cleaning		All types of contamination. Spalling of surface.	Hot oxyacetylene flame used.	Useful in some cases. May be used prior to grinding or blasting.
	Surface grinding or blasting		All types of fixed contamination. Abrasion and removal of surface.	Any of the usual techniques may be used. Work downwards.	It may be preferable to wet the surfaces first. Operator will require respirator.
Clothing	Vaccum cleaning		Useful for dry dust contamination.	Use small nozzle.	Sometimes useful prior to laundering. (See remarks under Brick and Concrete)
	Normal laundering (preferably soap, sodium pyrophosphate and carboxymethyl cellulose, otherwise usual detergents)		Best method for inert contamination.	Normal laundering methods. Soap and soft water far superior. Avoid excessively alkaline conditions. First wash at pH 10, following washes initially pH 8, rising to 10.	Means for effluent disposal required.
	Special procedures. Soap wash, followed by a soak in complexing detergent solution.	D	Best method of reactive contamination.	Usual laundering methods but with addition of a soaking stage. (Stir occasionally during soaking). Alternatively boil with complexing solution 15 minutes (see text)	Special chemicals required, but other methods will have little effect. Wool is more difficult to decontaminate than cotton and other fabrics.

Surface or Article	Decontaminating Agent	Ref. Sect. 8.8	Type of Contamination and Action	Procedure	Remarks
Waterproof Clothing (Rubberised and Oilskins)	Detergent	A	Inert dust and reactive contamination	Wash down and scrub any high spots, rinse down with water (Only cold or warm water is admissible)	Seams are liable to retain activity.
	Complexing detergent solution	C	Reactive contamination	As above. A long soak may be used if necessary. Preferable to use warm solution.	
	Fine pumice or other scouring powder	G	All types of contamination	Scrub with reagent and rinse well. Repeat if necessary.	Most effective treatment.
Canvas Rope, etc.	Vacuum cleaning		Dry dust contamination.	Use fairly small smooth nozzle.	Useful first step. See remarks under Brick and Concrete)
	Detergent	E	Inert dust and reactive contamination.	Scrub down, hot water if available, rinse off well.	Canvas and rope work are difficult to clean.
	Complexing detergent solution	C	Reactive contamination.	Soak with occasional agitation for as long as permissible, and as hot as permissible.	
Glass	Detergent	A	All types	A normal wash down or scrub if necessary. Work downwards.	Inspect any frame or mounting for holes prior to washing. If leaky frames are found, wash with damp cloth rather than with excess water.
	Complexing detergent	C	Reactive contamination.	As above. Use warm solution.	As above. This treatment should be necessary only in severe cases, or possibly in less severe cases where the glass is frosted.
Greasy Surfaces (In all cases where grease is present, most of the contamination will be removed with the grease)	Emulsifying Solvent Cleaners e.g. 1 part Lissapol NX 1 part Lubrol MOA, 9 parts Kerosene		All types of contamination adhering to grease and oil films.	Work cleaner into grease deposit to dissolve. Hose off cleaner and dirt with high pressure hose.	Economical and Effective. Preferred Method.
	Organic Solvents. (Trichlorethylene, white spirit, Petrol, Kerosene, Cresol, etc.		All types of contamination (reactive contamination will be relatively unreactive in these solvents and the danger of fixation of contamination will be less)	Usual techniques. Washing down, using swabs dipped in solvent. Bathing in solvent. Solvent spray, etc. In each case wiping of the surface is desirable. Vapour degreasing will not be as effective.	Usual precautions necessary in the use of these solvents must be observed. Means for disposal or recovery of these solvents will be required. In the case of clothing normal dry-cleaning will be of little use.
	Steam (with detergents if available)		Inert contamination mainly.	Work downwards from the windward side of work.	
	Hot detergent	E	Mainly inert contamination or reactive contamination if complexing agent is added.	Hot bath, spray, or hose depending on object and size.	Useful for light aluminium and magnesium alloys.
	Strong alkali with a little detergent	B	As above	Hot or boiling, bath or hose.	Not suitable for above metals. Avoid splashing and spray. Means of disposal required. Dilute if necessary.

Surface or Article	Decontaminating Agent	Ref. Sect. 8.8	Type of Contamination and Action	Procedure	Remarks
Hard grease and grime	Fine pumice or other scouring powder	F	All types of contamination. Abrasive	Rub on in paste or powder form, scrub if necessary. Wash off well. Work in small patches, one at a time.	Very effective where other methods fail. Suitable for small objects not of a precision nature.
Hair	Detergent	A	All types of contamination. Less effective for reactive contamination	Shampoo hair in warm water in normal way, repeat if necessary, rinse well	Any usual soapless shampoo is satisfactory.
	Complexing detergent solution	C	For reactive contamination left after above treatment	As above. Rinse well	Hair is difficult to decontaminate from reactive contamination. Usually safest to trim off hot locks.
Human Skin	Soap (Mild toilet) (Wood, flour or fullers earth may be added)		All types of contamination, especially inert	Wash well in soap and warm water scrubbing with a soft brush. Repeat until clean	Preferred procedure in all cases.
	10% Potassium permanganate, 2% Sodium bisulphite		All resistant contamination	Rub or swab on the permanganate solution for a minute or two, wash off, and decolourise with bisulphite applied similarly	Usually used only when the above fails. In the case of any cuts, wounds, sores, etc., medical attention should be sought.
Metals (see also Surfaces)	Hosing and brushing with water		Mainly inert contamination	See remarks for "Asphalt"	Useful for large areas
	Detergent	A	As above	See remarks for "Asphalt"	
	Organic Solvents and Emulsifying Solvent Cleaners		All types of contamination	See remarks for "Greasy Surfaces"	
	Complexing detergent solution	C	Reactive contamination	Wash down in normal manner	Suited to light metals which would be attacked by more severe treatments. (e.g. aluminium alloys)
	Fine pumice or other scouring powder	F	All types of contamination	See Remarks under "Hard Grease and Grime".	Suitable for all metals but not on precision parts
	Metal polish		All types of contamination	Usual method of application, change rags frequently	Suitable for small and delicate parts
Heavy metals iron and steel etc.	Industrial de-rusting agents, especially inhibited phosphoric and other acids	G	All types of contamination	Soak in bath with occasional brushing, hose down, or wash down with the solution. Rinse well afterwards, dry, and grease to prevent rusting.	Fast and complete decontamination. Acid should be handled with care and splashing avoided
	Sand blasting (preferably wet)		All types of contamination	For dry sand blasting a special box is preferable. Wet sand blasting less hazardous	Complete surface removal with accompanying damage. Contamination may be spread over large area. Suitable only for large rough objects.

Surface or Article	Decontaminating Agent	Ref. Sect. 8.8	Types of Contamination and Action	Procedure	Remarks
Paint	Hose and brush down with water		See remarks under "Asphalt"		First step in dealing with large areas, particularly in cases of inert dust contamination
	Detergent	A or E	As above		Run off water should be controlled, and not allowed to flow towards clean areas
	Complexing detergent solution	C	Reactive contamination	See remarks under "Asphalt". Use hot solution (Preferably PH5)	In case of buildings care should be taken to see that contaminated water does not flow into or be driven into an uncontaminated interior.
	Fine pumice powder or other scouring powder	F	All types of contamination	See remarks under "Hard Grease and Grime"	
	Trisodium phosphate		All types of contamination	Rub surface for a few minutes with rag moistened with hot 10% solution, wipe dry, use clean rag for subsequent application	Surface removed. As above
Stripping Agents	Steam (with detergent (if available)		See remarks under "Asphalt"		
	Strong alkali preferably with a little detergent	B	All types of resistant contamination	Soak surface or paint on, leaving for 1 to 2 hours, hot or cold, wash off, and scrape off any remaining paint	Complete stripping of paint. Not suitable for aluminium or magnesium alloys. Splashes should be avoided.
	Organic solvents, e.g. trichlorethylene, and industrial paint stripping compounds		All types of contamination	Immerse, wash and scrape or use usual methods of application in the case of industrial strippers	Should be used in a well ventilated space and usual precautions for solvents taken.
	Burning off		All types of contamination	Usual technique, burn and scrape	Useful for exterior paintwork window panes, etc., only. Hazardous.
	Sand blasting		See under "Heavy Metals etc."		Suited to hard finishes, e.g. vitreous enamels.
Plastics	Detergent	A	) See remark under "Glass"		
	Complexing detergent solution	C	)		
	Fine pumice powder or other scourer	F	See remarks under "Hard Grease and Grime"		
	Metal Polish		All types of contamination	Use in normal manner, replace rag at frequent intervals	Useful on hard smooth plastics, e.g. perspex and bakelite

Surface or Article	Decontaminating Agent	Ref. Sect. 8.8	Type of Contamination and Action	Procedure	Remarks
Leather	Water		Inert dust contamination.	Polished leather may be cleaned, by wiping with a damp cloth.	
	Brushing		As above.	A good brushing in the welts will help to remove dust from boots.	
	Organic Solvent		All types of contamination.	Wipe polished leather with a cloth dipped in a solvent will remove activity with the polish and oils.	Leather so treated should be repolished immediately.
	Wire Brush or Sanding		All types of contamination when dry.	A good stiff brushing with a wire brush will be effective in removing the surface layer.	Avoid dust. Suitable for soles and heels. Failing this, leather should be discarded.
Rubber	Detergent	A	Inert contamination mainly.	Good wash down, and scrub, preferably hot.	First step in decontamination of rubber.
	Detergent	E	Inert contamination held by grease.	As above.	This is preferable to the use of organic solvents.
	Organic Solvents, especially acetone. (not recommended for general use)		All types of contamination.	Swab over quickly, do not allow the solvent to remain in contact for long.	Not recommended for general use, suitable for greasy patches only.
	Complexing detergent solution.	C	Reactive contamination.	Soak goods in hot solution, or wash down. Length soaking is more efficient. Rinse well. (Rubber may be boiled in this solution with benefit)	Applicable to all types of rubber.
	Acids, industrial de-rusting agents, e.g. inhibited phosphoric acid.	G	All types of contamination, especially reactive.	Soak goods in solution for as long as permissible, or in case of large objects wash down. Brush. Rinse well.	Most rubbers are resistant to these compounds. Care will be required in their use, splashes should be avoided.
	Fine pumice or other scouring powder	F	All types of contamination.	Rub on in usual manner, wash off well.	Surface abrasion. More suited to hard rubbers.
Soil	Land scrapers and bulldozers		All types of contamination.	Soil should be damp but not wet.	Only method available. Means for burial or other disposal of large quantities are required.
Tile and Slate	Vacuum cleaning		Suitable for dry dust contamination.	See remarks under "Brick and Concrete"	Useful for porous and rough surfaces.
	Hose down and brush		Mainly inert contamination.	Work downwards, directing hose down slope. Brushing down will be an advantage.	Care should be taken to avoid the entry of water into uncontaminated building interiors.
	Trisodium phosphate or other strong alkali	B	All types of contamination.	Scrub hot 10% solution onto surface flush down with water.	Surface removal. Good for floor tiling.
	Surface grinding or blasting.		See remarks under "Brick and Concrete"		

Surface or Article	Decontaminating Agent	Ref. Sect. 8.8	Type of Contamination and Action	Procedure	Remarks
Wood (Unpainted	Vacuum cleaning		Mainly inert contamination	(See remarks under "Brick and Concrete"	Useful for flooring, especially rough surfaces.
	Scrubbing with Detergent	A	Mainly inert contamination.	Work downwards, avoid entry of water into uncontaminated areas and spaces.	Suitable for upright woodwork, weather-boarding, etc.
	Planing, scraping, sanding.		Suitable for all types of contamination. (Surface removal)	Conventional techniques. Preferable to wash down as above, and allow to dry prior to present treatment.	Suitable for floors, table-tops, etc. but laborious. (Dust hazard)

All the Tables in this Section are reproduced from A.W.R.E. Report No. 0-49/55 "A Guide to Radiological Decontamination after a Nuclear Explosion or Radiological Attack" (Official Use Only)

CHAPTER 9 - RADIAC INSTRUMENTATION

The term "RADIAC" is a contraction of the phrase "Radiation Detection Identification And Computation" and is an international and inter-Service term applied to instruments designed for use by personnel involved in atomic warfare, for various monitoring processes which are discussed below.

9.1. Types of Radiation.

The types of radiation emanating from a nuclear explosion have been discussed in Chapters 1-3 of this Part of the Manual, and definitions are given in Part II (Glossary).

There are four main types of nuclear radiations resulting from an explosion, namely:-

(a) Gamma-rays
(b) Beta particles
(c) Alpha particles
(d) Neutrons.

Of these radiations, alpha particles constitute a hazard which is likely to be met only in special circumstances, e.g. the disposal of unfissioned material, and hence the measurement of alpha particles is not included as one of the standard requirements for a Radiac instrument.

Beta radiation constitutes a definite part of the residual radiation from an atomic explosion, i.e. from the fallout. Considerations for and against including beta measuring facilities in Radiac instruments are discussed in Section 9.3.

Gamma radiation resulting from an atomic explosion may be considered in two categories. Firstly, that from the actual explosion itself ('prompt', 'initial', or 'immediate' gamma radiation), and secondly, that from the fission products which fall out ('residual' radiation). Radiac instruments are designed to measure gamma radiation.

Surplus neutrons from the fission process can escape from the actual explosion, and in the case of a comparatively low burst, can reach the ground.

In most practical situations the other bomb effects are more likely to be lethal than the neutrons, and so no provision is at present made for neutron measurement in Radiac instrumentation.

In the Armed Services and Civil Defence Service*, instruments are therefore required for the following purposes:-

(a) Measurement of doses of gamma radiation received by personnel.

(b) Measurement of dose-rates from the radioactive contamination of ground, etc.

(c) Measurement of dose-rates from the radioactive contamination on the clothing and bodies of personnel, and on vehicles, etc.

(d) Measurement of the degree of contamination on food and in drinking water.

(e) Measurement of radioactivity for specialised purposes.

(f) Training.

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* Subsequently in this chapter, "Service" will imply the Armed Services and Civil Defence.

9.2. Measurement of Personal Doses (Flash Dosimeters)

There are two types of radiation dose which are important to the individual - initial radiation received from the actual explosion, and residual radiation, received from the radioactive cloud or from fallout deposited on the ground.

It has been stated (reference Chapter 2) that a single dose of 450 roentgens will cause the incapacitation within 24 hours of all who receive it, and ultimately the death of about 50% of the recipients. An instrument is therefore required that will measure doses of gamma radiation of up to (say) 500r when emitted at a very high dose-rate. Such instruments have been termed "Flash Dosimeters" and may be of several types, described in Table 1. While all the following principles are theoretically sound, work in the U.S., Canada and this country has shown that several methods are unsuitable for Service use. Comments on this are given in the last column of the table.

Of the types listed in Table 1, only 'd' and 'e' - the Phosphate Glass and Quartz Fibre Dosimeters - are in British Service use.

The dose-rate at which doses from residual radiation are received is very much lower, and any instrument designed to work under high dose-rates will operate in these lower conditions. However, the dose to be measured is also appreciably lower. The flash dosimeter is intended basically for use by Service or emergency medical organisations to enable assessment of the correct treatment, and by the Commander in the field to assess the fighting potential of his troops. A dosimeter intended for measuring residual radiation (or radiation from a radioactive source or reactor) is intended to give a measure of the radiation received by an individual, and so ensure that he does not receive more than the tolerable dose for the particular circumstances. Thus a radiation worker in an establishment using a reactor or in a store holding radioactive sources would be restricted to 0.1r per week, while troops in the field or Civil Defence personnel in an emergency might have to be subjected to a single dose of 25r or even higher.

For reasons of sensitivity only photographic, phosphate glass and quartz fibre types of flash dosimeter are suitable for measuring doses of less than 50r. The photographic dosimeter is unsuitable in the field, as already stated, for technical reasons.

The Phosphate Glass dosimeter is suitable for Service use where incremental doses of (say) 10r or more, are of importance.

The Quartz Fibre dosimeter (designed so that the instrument is of the correct range) will cover any maximum dose from 0.5r to 500r, or even higher. Selection of a suitable range is therefore possible. Thus workers in Ordnance Depots holding radioactive sources use the 0 - 0.5r instrument; troops in the field would carry the 0 - 50r or 0 - 150r instruments as well as the 0 - 500r.

The term "Flash Dosimeter" has been used here to describe a dosimeter suitable for use in measuring initial radiation, i.e. that received at a very high dose-rate. The official Service terms "tactical", "residual" and "technical" are used to denote dosimeters of varying ranges and uses. Broadly speaking the tactical dosimeter is intended for measuring the large doses of radiation received at high dose-rates from the actual

nuclear explosion and enables a quick assessment of the fighting potential of the troops to be made. The residual dosimeter is used to measure the gamma dose received by its wearer when operating in a radioactively contaminated area. The technical dosimeter is used to measure the dose received from low activity radioactive sources and, as such is worn by personnel handling training sources etc.

TABLE 1 - Types of Flash Dosimeter

Type	Principle	Comments
a. Photo-graphic	Ordinary film, (in this case "dental film" used for X-ray photographs of teeth) is blackened on exposure to gamma radiation. The density of the blackening can be measured and converted to a measurement of dose.	This method is used in Atomic Energy Establishments etc. where processing may be done under controlled conditions. "Service" types incorporating a developer are not particularly suitable and have tended to be rejected in favour of better principles. Low cost.
b. Chemical	Gamma radiation will cause the formation of HCl from a mixture of a chlorinated paraffin (e.g. carbon tetrachloride) and water. The amount of HCl formed, expressed as a pH value is related to the dose and may be measured by the colour change of suitable indicators.	Used in the U.S. - Individual Dosimeter E1R3, consisting of five tubes designed to change colour at 50, 125, 175, 300 and 450r respectively. Dosimeter reacts to sunlight and is generally not very reliable. Fairly low cost.
c. Crystal	Crystals of alkali halide (e.g. potassium chloride) become coloured on exposure to gamma radiation. Colour may be matched against samples mounted contiguous to the crystal or on some colorimeter.	Colour matching by eye is difficult as it is only the depth of colour that is affected by additional doses. Provision of a colorimeter would increase the cost. Crystal bleaches in strong light which is a disadvantage although it means that the crystal can be intentionally bleached and re-used.
d. Phosphate Glass	A phosphate glass activated with a small quantity of silver, will fluoresce under U.V. light after irradiation by gamma-rays. The fluorescence is measured and compared against a standard, the ratio being converted to give a meter-reading in roentgens. The reader can be operated from the mains or other equivalent supplies powered by wet batteries. Operation from dry batteries would require a special design of reader with low current consumption.	Dosimeters cost about 5s.0d. but reader costs about £150. A satisfactory type of dosimeter where incremental doses of less than about 10r do not have to be measured, i.e. on operations.

Type	Principle	Comments
e. Quartz Fibre Dosi-meters	Consists of an ionisation chamber to detect the radiation, with a gilded quartz fibre electrometer which is read through an optical system built into the dosimeter. The instrument which is normally the size of a large fountain pen is charged up to read "zero". Gamma radiation causes the dissipation of a proportion of the charge, the amount being read on the electrometer as a reading in roentgens. Chargers may consist of a source of H.T. from batteries (i.e. a 150 volt battery or a L.T. battery and vibrator or transistor unit) or an electromagnetic unit incorporating a hand generator. The last type is used in British chargers. Some means of transferring the charge from the charger to the dosimeter and of adjusting the charged dosimeter to read zero must be incorporated.	Cost about £5 each. Very robust. Owing to difficulties in collecting all the ions formed in the ionisation chamber when the instrument is exposed to higher dose rates, these dosimeters tend to under-read when measuring full-scale doses of 'prompt' radiation, if their scales have been calibrated on doses applied more slowly. The correction factor on an existing design of 500r dosimeter (the QF No.5) is about x1.4, but it is feasible to design 500r dosimeters with substantially complete collection under flash radiation conditions.

9.3. Measurement of Contamination of Areas (Survey Meters)

Instruments designed for reconnoitring and surveying contaminated areas are now known as "Survey Meters". This is an inter-Service and standardised NATO term which replaced the old U.K. term "Portable Dose-Rate Meter".

In view of the fact that a dose of 25 roentgens can be accepted as a military tolerance in operational conditions, and also the fact that the activity of the fallout of an atomic weapon decays according to the $T^{-1.2}$ law, the ranges required on the Service survey meter are probably 0.05r/hr to 300r/hr, but the majority of readings will not exceed 3r/hr.

Measurement of dose-rates such as these can be easily carried out with a simple ionisation chamber/electrometer valve circuit, in which the ionisation current is used to develop a voltage across a high value resistor in the grid circuit of a specially designed triode called an electrometer valve. Any change of this voltage is measured by a microammeter in the anode circuit. The usual principle is to use three different grid resistors varying by 10:1 ratios and hence have three ranges on the instrument, e.g. 0 to 3, 0 to 30, and 0 to 300 r/hr.

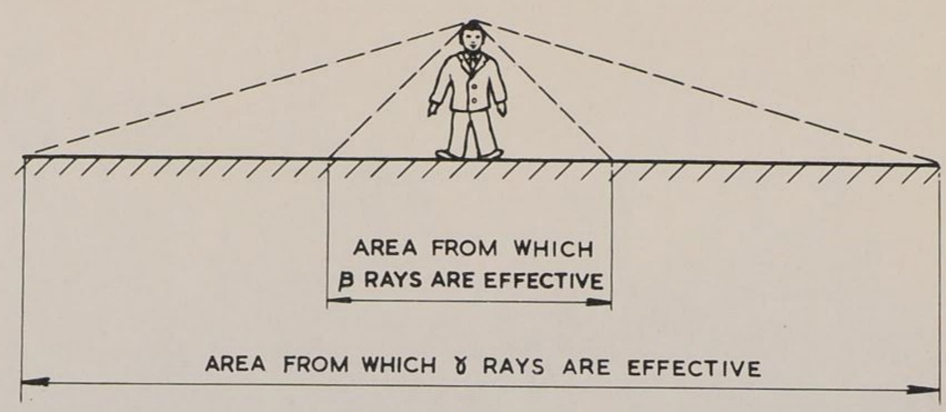
As an alternative to this, the pseudo-logarithmic characteristic which results from a free grid circuit may be used. In this circuit the ionisation chamber current is balanced against the grid current, the change in anode current being measured by a meter. In this type of meter the three decades 0.5 r/hr to 500 r/hr may be read without switching.

In their basic design, survey meters are sensitive to gamma radiation only, as the ionisation chamber is usually enclosed in a metal or plastic case. If however, the ionisation chamber has one side closed with a thin window (of surface density not exceeding about 40 mg/cm^2), then any beta particles incident on this window with energy exceeding a certain threshold will penetrate the window and cause ionisation in the chamber. It is therefore possible for the instrument to indicate the presence of beta radiation. If some form of shutter is fitted to the beta window, it is possible in a given field to obtain a measurement of the gamma dose-rate when the shutter is closed and an indication of the beta + gamma dose-rate when the shutter is open. (The beta hazard is of some importance with fission product activity.) The ratio of beta dose-rate to gamma dose-rate will depend on the terrain over which the measurement is taking place since the beta radiation is of less effective range than the gamma. Hence, in the two circumstances shown in Figure 1, in (a), the man is receiving gamma radiation from a distance as well as from his immediate vicinity, while the beta radiation is received effectively from his immediate neighbourhood only. In (b), the gamma dose-rate is appreciably reduced by the surrounding buildings while the beta dose-rate is the same. Thus an instrument which measures gamma radiation only will give a lower reading in case (b), while in fact the beta dose-rate is the same. If therefore an estimate of the latter is based on a particular beta/gamma ratio, an erroneous conclusion will be formed in one case.

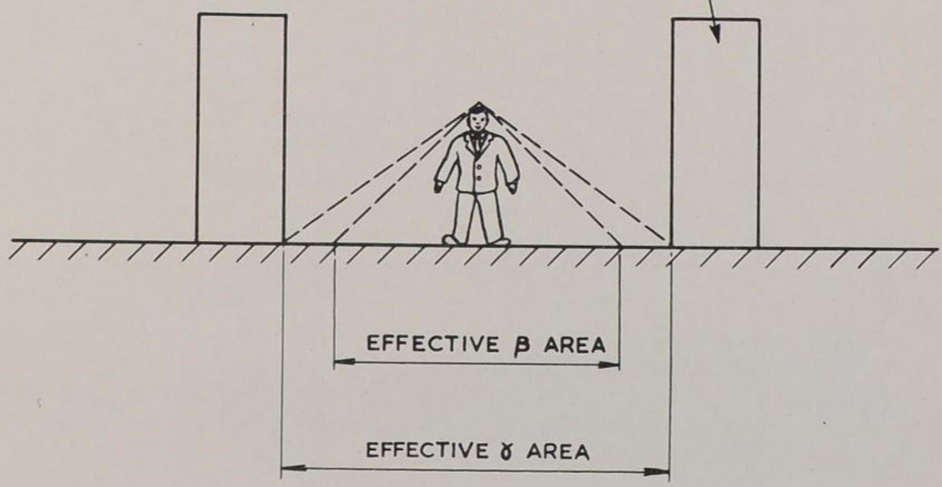
In addition, the beta/gamma ratio depends also on the beta energy spectra of the fission products, which vary with time. Typical figures for beta/gamma ratios for plane surfaces are 15:1 a few hours after burst, dropping to 4:1 after three weeks, and then rising slightly after three months.

The beta dose associated with a gamma dose of 25r is estimated to be about 300 rep, and hence the beta hazard will not normally be in excess of that estimated from the gamma hazard. However, these ratios apply to measurements at about three feet from the ground. In cases where the fission products are in contact with or close to the skin, e.g. when a man is lying down, the figures are much higher - figures of over 100:1 have been mentioned. In these cases, the beta hazard may exceed the gamma hazard, but may still be estimated from the gamma measurement if certain basic assumptions are made.

A certain degree of interference from radar is experienced by ionisation chamber instruments that are not screened, i.e. have non-metallic cases. The interference occurs mainly in the centimetric and millimetric bands (10,000 Mc/sec - 3,000 Mc/sec) and may manifest itself as either a negative or a positive reading. The trouble occurs only when the instrument is in the direct beam of the radar set and then only when within (say) 200 yards of it. It can be prevented by encasing the instrument in a metallised bag or in a thin metal carrying case.



(a) RELATIVE EFFECTIVE AREAS IN OPEN



(b) SITUATION IN BUILT-UP AREAS, IN SHELL HOLES ETC., WHERE THE β RADIATION IS THE SAME AS IN (a) BUT THE γ RADIATION IS MUCH REDUCED

EFFECT OF TERRAIN ON RELATIVE BETA AND GAMMA RADIATION HAZARDS

9.4 Measurement of Contamination on Personnel, Food and Water (Contamination Meters)

The hazard from contamination of the skin and clothing is mainly a beta radiation hazard, but may be estimated in terms of the response of a gamma-sensitive instrument held at a standard distance from the body. If this distance is chosen as 50 cm. then an instrument measuring up to 50 mr/hr. is required in order to discriminate between excessive contamination and that which is permissible by emergency standards.

Instruments meeting these requirements are called Contamination Meters. In view of the sensitivity required, an instrument incorporating a Geiger-Mueller tube is desirable. The Geiger-Mueller tube is a form of ionisation chamber working at a polarising voltage sufficiently high that each individual ionising event in the tube will initiate a discharge of standard size in the tube. The meter consists of the necessary amplifying circuit together with a pulse counter or a counting-rate meter. In the Service instrument, a counting rate meter is used and there is a facility for using earphones as well. The aural indication is an added help to the monitor as the increase in the well-known Geiger "clicks" in the earphones will call his attention to the high rate being shown on the dial.

Geiger-Mueller tubes, like the ionisation chambers of Survey Meters, will admit beta particles only if the walls of the tube are thin enough. As the G.M. tube is usually of glass, it then becomes very fragile and so a beta-sensitive tube is normally fitted into a probe with a metal "can' around it. A sliding window is opened to make the instrument beta-sensitive. In the case of British Service 'field' instruments the tube is sensitive to gamma radiation only, the beta hazard being estimated from the gamma measurements.

To measure the contamination on the person, two methods may be used:-

(a) the probe is placed at about waist height and the subject under test rotates once at a point about two feet in front of the probe, or

(b) the probe is used as a 'frisker', i.e. is run over various parts of the body in turn.

Both methods are possible with the current Service instrument.

The use of a Geiger counter instrument for this purpose has xcertain disadvantages however. The usual method of measuring contamination on the person, described as method (a) above, involves a fairly sensitive instrument, as it has to measure the activity from a comparatively small amount of contamination two feet away. This results in the instrument being very sensitive to a gamma background and in practice a background exceeding about 2 mr/hr. will effectively mask any readings. It is possible to erect shielding around the instrument, but as this shield has to be large enought to enable the subject under test to move around inside, it will be appreciated that a fairly large sandbag edifice will be required.

It is therefore preferable to use a less sensitive instrument which has to be held closer to the contamination. This has the effect of enhancing the reading from the contamination and minimising the

/background

reading. Trials at Operation Buffalo indicated that an ionisation chamber instrument of design similar to the Survey Meter No. 2, with a beta-sensitive ionisation chamber, was capable of being used as a 'frisker' in quite high backgrounds. As an example, a degree of contamination which would give slightly under a full-scale reading on the Contamination Meter No. 1 used as in method (a) above, gave a reading of 1.5 r/hr. on the Survey Meter No. 2 used as a 'frisker' with its beta window open. The background was 100 mr/hr - ten times full-scale on an unshielded Contamination Meter No. 1 but only 1/30 full scale on the bottom scale (0 to 3 r/hr) of the Survey Meter No. 2.

The advantage of using a beta-sensitive instrument is two-fold; firstly, the range of the beta particles is sufficiently small that the instrument can delineate the boundaries of the contamination more accurately, and secondly, the ionising capabilities of beta particles are greater than for a similar number of gamma photons, hence an enhanced reading is obtained. The scales of instruments calibrated for gamma radiation only indicate the degree of beta radiation, and do not measure in any particular units.

As a result of this, future policy, at least for the Army, will be in terms of a combined Survey/Personal Contamination Meter as it will be technically possible to combine the two instruments. This is also very convenient tactically.

A sensitive instrument is required for monitoring food and water, as the degrees of contamination liable to prove hazardous on ingestion are relatively low.

The Contamination Meter No. 1 is suitable for this purpose, and is used as a 'frisker' for measuring the contamination on food.

To measure the contamination in water, the probe may be held at a fixed distance from the water, or alternatively, a special beta-sensitive G-M tube into which a sample of the water may be poured, can be used.

Special devices have been developed to measure long-lived alpha activity in personnel, food, air and water.

9.5 Measurement of Radioactivity for Special Purposes

In the field it will be necessary to have some instrument for measuring beta and gamma activity with greater accuracy, and for measuring alpha activity. A specific case is in the Army Mobile Pathological Laboratory, and similar instances will occur in the other Services.

As an example, an alpha, beta and gamma sensitive monitor, built to Service specifications as regards robustness, water tightness, etc. has been developed from the standard A.E.R.E. Health Monitor No. 1021. The instrument is described in Table 1 of Section 9.7; such an instrument must incorporate alpha, beta and gamma sensitive probes, and preferably a counting device measuring the number of disintegrations in unit time rather than a dose-rate.

It may be necessary in order to combine the greater accuracy with the robustness required in a Service instrument, to accept a lower degree of portability than is usual in field instruments.

Special instruments have also been devised for training purposes. Training devices may be in two categories - (a) those which work on the same principles as their 'parent' instruments but which are very much more sensitive in order to avoid undue exposure of trainees to radiation, and (b) those which superficially give an apparent measurement of (say) dose-rate on a dial but in fact operate on a completely different principle. They are described here as in some instances they are useful instruments for purposes other than their principal one.

Radioactive devices - Training must include practice in the use of the Survey Meter, Contamination Meter and Dosimeter. The present set of training devices consists of a series of radioactive sources of different strengths, held when not in use in special shielded containers. The dose rate from these sources is insufficient to operate the normal survey meter, and so a specially sensitive Geiger-Mueller tube instrument called a "Portable Dose-Rate Meter Trainer" has been developed. This will give a full dial reading on the meter in a field causing virtually no hazard to the operator. Similarly a 0 to 0.5r dosimeter has been developed for the operator to wear during training.

For practising the use of contamination meters, a special source that could be carried on a man has been produced. This emits gamma radiation only and is of a size that will not constitute a serious hazard.

Simulators - Two alternatives are possible to simulate the radiation from fallout. The first is a radio transmitter with receivers designed to look like survey meters but in fact with the dial measuring an amplified aerial current. The second is a modification of the leader cable used for bringing aircraft into airfields. This device, known as the Radiac Fallout Simulator, makes use of the alternating magnetic field associated with a conductor carrying an alternating current. Cable arrays carying a 1,000 cycles per second to 5,000 cycles per second current can be laid out to give a magnetic field whose pattern resembles that of the fallout from a low air-burst atomic weapon. Here again the "receivers" are designed to resemble superficially a normal Survey Meter.

9.6 Service Requirements

9.6.1 Storage and Durability

All Radiac instruments accepted into the Services are subject to the Inter-Service Specification on Climatic and Durability Testing, No. K. 114, and are therefore of the same order of robustness as (say) wireless sets intended for field use or for fitting into aircraft.

In general, instruments such as Survey Meters and Contamination Meters are sealed to prevent gross ingress of damp or dust, and are fitted with a desiccator incorporating a colour indicator.

Other instruments such as the Charging Units for dosimeters have their electronic components mounted into a capsule to prevent the entry of damp or dust.

The main trouble which is likely to arise with any instrument which is powered by batteries is the shelf-life of the batteries and the physical decay of the batteries if left inside the instrument. The question of shelf-life of batteries is, of course, applicable to all instruments using batteries. The physical decay of the batteries in the instruments is obviated by ensuring that no instrument is stored with batteries in it, or is put away with the set switched on. Run-down batteries, particularly those run down at a high current (e.g. a lamp battery), are prone to bursting. It will be appreciated that the effect of a broken-down Leclanché cell on an aluminium die-casting is highly deleterious.

Leclanché cells have the disadvantage of becoming virtually useless when their temperature drops much below freezing point. To obviate this, some instruments can be supplied with adaptors which enable the battery pack to be carried in the operator's pocket, using his body warmth to keep the batteries at a workable temperature.

Radiac instruments should be stored under conditions similar to those in which Service Wireless Sets are stored.

Ionisation chamber instruments, i.e. Survey Meters and Q.F. dosimeters, are dependent on the amount of air in the ionisation chamber. In general all instruments of this type are dependent on gross changes of atmospheric pressure, e.g. an appreciably diminished reading would be obtained when operating the instrument at heights above a few thousand feet, e.g. in mountainous areas or aircraft. Allowance must be made for this by suitable calibration.

Trials on Radiac Instruments at Operation Buffalo showed that the instruments would stand up to the wear and tear to be expected in the field.

9.6.2 Calibration

The general principles of calibrating a Radiac instrument comprise a method of zeroing the instrument and a method of ensuring that it gives the correct reading for a given dose-rate or dose.

The calibration sensitivity of Q.F. dosimeters cannot be adjusted after manufacture. During inspection, dosimeters (if they are of a type that can be reset to zero) are tested to ensure that they are within the tolerance for accuracy.

All Survey Meters and Contamination Meters have a built-in method of resetting the zero, so that this operation may be performed immediately before the instrument is used.

Calibration is usually carried out by holding the instrument (or probe, in cases where this is separate) in a jig and exposing it to a radioactive source which is known to give a certain dose-rate to the instrument. These calibration jigs are supplied as Service stores to the appropriate Maintenance Units.

In instruments where high dose rates are measured, the use of radio-active calibrating sources is impracticable and an electronic means of calibrating is used instead. This method uses a means of feeding into the measuring circuit a current equal to that which would be fed in by the ionisation chamber when exposed to a given dose-rate.

Full details of zeroing and calibrating instruments are given in all instrument handbooks.

Radiac instruments are designed to maintain their calibration for considerable times, and generally need re-calibrating only when a component is changed.

9.6.3 Response time

All dose-rate measuring instruments have a definite response time which is dependent on the time taken for the ionisation chamber or G-M tube to reach a state of equilibrium.

In some cases, especially with low dose-rates, this time may be sufficiently large to preclude the use of the instrument when the speed of passing the contaminated person or area is too great. For example, a Survey Meter used in an aircraft flying at (say) 200 feet, might fail to record a heavily contaminated patch before the aeroplane had flown beyond it. Similarly, if personnel or vehicles parading in front of a contamination meter were to pass by too quickly, the meter might fail to detect any contamination.

Response times vary considerably from instrument to instrument, but are adequate for the purpose for which the instrument is primarily designed.

With all direct reading instruments, e.g. Q.F. dosimeters, survey meters, and contamination meters, the dose or dose-rate can be determined in about the usual time taken to ready any dial. Non-direct-reading instruments such as the other types of disometer require to be returned to some base or headquarter unit (it may only be as far back as a battalion H.Q.) for "processing" and reading.

9.7 Details of Current Radiac Instruments

The specifications for current Radiac instruments include such requirements as:-

Climatic, Rough Usage and other Inter-Service tests
Portability
Response to radiation of different energies
Response to different dose rates
Accuracy of recording.

Generally, the "technical" requirements such as response and accuracy are a compromise between those which can be obtained in a laboratory instrument and the need for Service conditions to be met.

Detailed specifications for each instrument are available (see bibliography below) but Table 1 gives information regarding ranges etc. It can be assumed that for use in atomic warfare, that part of the radiation (as regards energy, etc.) which is of significance to man, is always recorded.

In Table 1 details of current instruments are given together with their Inter-Service numbers, their A.E.R.E. numbers, the Services who use them, and any remarks. The list includes all major Radiac instruments but does not record every small part even though it may have a separate Inter-Service catalogue number.

The development of Radiac instruments for all Services is the responsibility of D.L.R.D., Ministry of Supply. The design authority for all these equipments is the Atomic Energy Research Establishment, Harwell.

No transistors are used in any current designs of Radiac instruments. One of the chief reasons for this is that the upper limit of temperature specified in the climatic specifications laid down by the Armed Services has, until recently, been too close to the working limits of suitable transistors for safety.

At Operation Buffalo, a team of six Army Officers carried out a series of trials on Radiac instruments and methods, and a reference to the Team's report is given in the Bibliography. Generally speaking, the instruments behaved quite satisfactorily and gave readings which were within specification tolerances.

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S.I.M.A. Catalogue "Radio Isotope Instrumentation and Accessories" - The Scientific Instrument Manufacturers Association

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A.E.R.E. Specifications and Instruction Books - S & M Section, A.E.R.E., Harwell, Didcot, Berks.
I.E.M.E. Handbooks - I.E.M.E., "Aquila", Bickley, Bromley, Kent.

All documents mentioned above are unclassified unless otherwise stated.

TABLE 1 - Current Radiac Instruments

Item	Name	Joint Services Catalogue No. 6665-99-911-	A.E.R.E. No.of Prototype	Capabilities	Services using instrument	Production Situation (May '57)	Remarks
1	Dosimeters QF No.1, 0-.5r " " 1A, 0-.5r	-0001 -0272	 1183A	Will read doses of 0 to 0.5r	R.N., Army, R.A.F., C.D.	S	Used for training and for stores holding R/A sources
2	" " 2, 0-5r " " 2A, 0-5r	-0002 -0101	1184A 1184D	Will read doses of 0 to 5r	"	S	
3	" " 3, 0-50r	-0003	1185A	Will read doses of 0 to 50r		P	
4	" " 4A, 0-150r	-0269	1433A	Will read doses of 0 to 150r		P	
5	" " 5, 0-500r	-0228	1434A	Will read doses of 0 to 500r		P	
6	Charging Unit No.1 Dosimeter, Quartz Fibre	-0004	1202A	Will charge dosimeters Nos. 1 to 5	All Services (Army for training only)	S	Has switch for transferring increments of charge to dosimeter. No facility for discharging.
7	Charging Unit No.2 Dosimeter, Quartz Fibre	-0189	1381A	Will charge dosimeters Nos. 1 to 5	Army	P	Has switch for adjusting charge on dosimeter.
8	Dosimeter Phosphate Glass	-0128	-	Will read doses up to 600r delivered at 'flash' rate or less	R.N.	U/D	Requires special reader.
9	Reader, dosimeter phosphate glass	-0129	-	Will read phsophate glass dosimeters directly	R.N.	U/D	Requires mains supply Used for reading Item 8.
10	Meter portable dose rate No.1	-0007	1038B	Reads 0 to 3 r/hr Fitted with beta window	Army, R.A.F. C.D.	S	Now being replaced by Item 11.

Item	Name	Joint Services Catalogue No. 6665-99-911-	A.E.R.E. No.of Prototype	Capabilities	Services using instrument	Production Situation (May '57)	Remarks
11	Meter Survey Radiac No.2	-0008	-	Reads 0 to 3, 0 to 30 and 0 to 300 r/hr. Fitted with beta window	Army, R.A.F. C.D.	P	
12	Meter portable dose rate trainer No. 1	-0010	1191B	Reads 0 to 3 x 10^{-4} r/hr	Army, R.A.F. C.D.	S	Superficially resembles Item 10
13	Meter Survey Radiac No. 3	-0123	1324A	Reads 0 to 30, 0 to 300 and 0 to 3000 mr/hr	Army, R.A.F.	P	For use in stores holding R/A sources
14	Meter Survey Radiac No. 4	-0124	1349A	Reads 0 to 15, 0 to 150 and 0 to 1500 mr/hr	-	-	Beta/gamma sensitive. Mainly for trials use.
15	Meter Contamination No. 1	-0012	1092D	Reads 0 to 10 mr/hr with gamma probe and 0 to 10 mr/hr. with special beta sensitive liquid (re-entrant) probe.		S	All contained in one haver-sack. Powered by H.T. batteries OR L.T. batteries + vibrator OR Mains
16	Monitor Radioactivity No.1	-0258	1257B	Sensitive to α, β and γ radiation. Reads in counts/sec.	Army, R.A.F.	S	Mains operated. Service version of A.E.R.E. 1021. Title is that used in Army; other Services may vary.
17	Source Radioactive A No.1	-0015	1210A	0.5 mC of Radium. Gives 0.5 mr/hr at 1 yd.	All	S	Used for checking instruments
18	Source Radioactive B No.1	-0016	1210A	100μC of Cobalt. Gives 0.16 mr/hr at 1 yd.	All	S	Used for wearing as "contamination"
19	Source Radioactive C No.1	-0017	1210A	1 mC of Cobalt. Gives 1.6 mr/hr at 1 yd.	All	S	Used for demonstration and training

Item	Name	Joint Services Catalogue No. 6665-99-911-	A.E.R.E. No.of Prototype	Capabilities	Services using instrument	Production Situation (May '57)	Remarks
20	Source Radioactive D No.1	-0018	1210A	5 mC of Cobalt. Gives 8 mr/hr at 1 yd.		S	Used for demonstration and training.
21	Source Radioactive E No.1	-0019	1210A	25 mC of Cobalt. Gives 40 mr/hr at 1 yd.	All	S	Used for demonstration and training.
22	Source Radioactive F No.1	-0025	-	25 mC of Cobalt	All	S	Used for calibrating instruments.
23	Source Radioactive G No.1	-0041	-	5 mC of Cobalt	All	S	" " "
24	Slide rule Radiac No. 1	-0027	-	Will calculate future or past dose according to $T^{-1.2}$ law.	R.N.	S	
25	Radiac Calculator No. 1	-0060	-	" " " " "	Army, R.A.F. C.D.	S	
26	Water Contamination Calculator No.1.	-0057	-	Will calculate hazard due to drinking contaminated water, knowing time after burst	Army, R.A.F. C.D.	S	Obsolescent for Army and R.A.F.
27	Meter Survey Avo, No. 1	NYA	1219	Reads up to 500 r/hr. on logarithmic scale		U/D	Alternative 100 r/hr. F.S.D. being developed for C.D.
28	Radiac Fallout Simulator	NYA		Will give magnetic field resembling "fallout" field	-	U/D	Two models giving "fields" up to 1000 yds. and 5 mls. respectively. Requires special "Survey Meter"

Item	Name	Joint Services Catalogue No. 6665-99-911-	A.E.R.E. No. of Prototype	Capabilities	Services using instrument	Production Situation (May '57)	Remarks
29	Test set, current sensitivity No. 2	-0112		Testing Item 11	Army, R.A.F. C.D.	S	

Abbreviations: NYA - Not yet allocated
U/D - Under development, P - In production, some available in Service, S - Produced and in service.

Note: The full J.S.C. No. for these instruments is in the form of a 13-figure reference, e.g. the J.S.C. No. of the Meter.

Survey Radiac No. 2 is 6665-99-911-0008

D1/57
September 1959.

Part VIII
Chapter 2
Preliminary

Chapter 2. Photographic Materials and Equipment.

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2.1 Introduction.

Photographic materials and equipment, being of a relatively delicate nature, may usually be assumed to have been rendered unserviceable when the buildings or vehicles which contain them suffer moderate or light damage. Moreover, photo-sensitive materials are liable to fogging by nuclear irradiation prior to processing. This is because, in addition to their sensitivity to visual light, photo-sensitive materials are also among the most sensitive means of detection of nuclear radiation. In this chapter we shall deal only briefly with the gross effects, and then only in so far as they are special to photographic equipment and materials; reference should be made to the appropriate previous parts of this Manual for consideration of the relative damage mechanisms for buildings, wrapping materials, etc. A more detailed examination will however be made of the effects of nuclear irradiation upon the photo-sensitive materials, such as photographic films and plates, and photographic printing papers.

General effects. Photographic equipment and materials are especially vulnerable to the effects of nuclear weapons in the following respects:-

(a) Mechanical damage. - Relatively slight mechanical damage permitting ingress of light either from the flash of the bomb or from ambient lighting. This would apply to cameras, photographic dark rooms, packages of materials etc.

(b) Thermal Damage - Scorching or charring of wrappings or of materials could permit the entry of light, as also could temporary warping, for example camera parts under the influence of the heat flash.

(c) Nuclear Radiation Damage - In addition to their effect on photo-sensitive emulsions, large doses of nuclear radiation can discolour glass, optical glass being particularly vulnerable in this respect. Considerable doses of nuclear radiation are required for this discolouration to be appreciable, so that it would only be significant in the case of equipment extremely well protected from mechanical damage. Any film in the equipment at the time would of course have been rendered completely useless, but there is the additional question of the future usefulness of the optical system itself. It may be noted that this problem is common to other optical equipment such as sights, telescopes etc. The doses required to produce this type of damage are given in Part VII, Chapter 4 of this Manual, and in Reference (1).

Reference (1) A.W.R.E. Report T.35/58. Operation Antler. Neutron-Induced Activity in Materials Used in Items of Military Equipment. (Confidential).

2.2 Nuclear radiation damage mechanisms.

2.2.1 Prompt effects - near the weapon. Both prompt and delayed nuclear radiations effect photo-sensitive materials, such as films, plates and to a much less extent, papers. Prompt effects are mostly confined to the general locality of the burst, in contrast to the delayed effects associated with fallout. As already noted, damage by prompt radiation will only be of military significance in the case of materials protected from the effects of blast and of heat or (in peace-time) in the case of trials of nuclear weapons, where considerable photographic equipment may be employed for target response recording purposes quite close to the point of burst. There are several possible mechanisms whereby the nuclear radiations can damage films etc. All the radiations result in some degree of fogging of the emulsion and are thus harmful only to undeveloped materials.

It must be borne in mind that this is a purely physical effect, so that the relevance of many of the statements made about nuclear radiations needs careful consideration, as much of the literature deals with biological targets.

Damage to undeveloped photo-sensitive emulsions could result from:-

(a) Fission neutrons from the bomb, mostly having lost energy by collisions in the bomb debris, or subsequently.

(b) Prompt gamma radiation from the bomb and from very short-lived fission products, augmented by the gamma radiation resulting from the scattering and capture of neutrons in weapon, air, or target environment.

(c) Beta radiation from neutron-induced activity near the target.

(d) Heavier charged particles such as fast protons, deuterons and alpha particles, arising from neutron capture - mainly by light elements - very close to the photo-sensitive emulsion.

Chemical elements particularly liable to give rise to (c) or (d) are tabulated in Part VII, Chapter 8 of this Manual, and more fully in References (1) and (2).

References (1) A.W.R.E. Report T.35/58 Operation Antler. Neutron-Induced Activity in Materials Used in Items of Military Equipment. (Confidential).

(2) D.A.W.Plans Note 15. Neutron-Induced Radioactivity. (Confidential).

2.2.2 Delayed effects - fallout. - In addition to the effects produced locally by the prompt nuclear radiations at the time of burst of an atomic weapon, trouble may also be experienced from the effect of the less intense but more continuous delayed radiations from fallout. This is because photographic materials have the property of integrating their total exposure to such radiation. There are two aspects of the problem depending upon whether or not the active particles come into actual contact with the photographic emulsion. If there is no such contact, then the main hazard is from the gamma radiation from the fallout, the relatively short range beta radiation being screened off by the

wrappings or by the photographic equipment itself. This gamma radiation would give rise to a general fogging of the whole film. If however the fallout particles can come into direct contact with the photographic emulsion then there will be heavy localised exposure to beta radiation, even perhaps to alpha radiation, leading to spots on the film, plate or paper, rather than to a general fogging. The various ways in which these two types of hazards may arise are considered in Section 2.3 below.

2.2.3. Assessment of overall effects due to nuclear radiations.

Most practical cases involve more than one mechanism of nuclear fogging, and often by more than one type of nuclear radiation. Because these effects depend upon environmental conditions in different ways, it is not possible to give a general relationship between the proportions of radiation of the various types and the yield and distance from burst of nuclear weapons.

The overall effect in an individual case is to be derived by summation of the various contributions to the fogging. Bearing in mind that in most cases the sensitivity curve of the photographic material will be very far from linear at the levels in question, it is realised that an exhaustive analysis of these lines may be tedious, but no easier basis of assessment has been suggested.

Basic data required in a particular case are thus:-

(a) A measure of the intensity on the photographic emulsion of the radiation fields due to the relevant nuclear radiations.

(b) A knowledge of the sensitivity curves of the emulsion in question, to each type of nuclear radiation concerned (ideally also as a function of energy). Such data as have been located are summarised in Section 2.3 below.

(c) An ordinary optical sensitivity curve (usually known as the characteristic curve) to enable the sum of the fogging contributions from (b) to be determined in relation to the normal degree of background fogging. These are available in the manufacturers literature. Some examples are given in Figure 1, at the end of Section 2.3 below.

In addition, the user will have to decide on the relationship between fog level and utility for the proposed application. This subject is discussed in Section 2.4 below.

If the routine precautions indicated in Section 2.5 do not serve to bring the situation within bounds, one or more of the techniques outlined in Section 2.6 may have to be employed.

A detailed note on the protection of aircraft photographic equipment against radioactivity is given in Reference 1.

Reference (1) D.A.W. Plans Note No. 16. "Military Air Photography and Nuclear Weapons", (Secret).

2.3 Sensitivity curves for certain photographic materials.

2.3.1. Examples of optical sensitivity curves.

Some typical optical sensitivity curves (or characteristic curves) for photo-sensitive materials are shown in Figure 1. Apart from the obvious difference in photographic sensitivity between emulsions prepared for various purposes, certain broad characteristics are common to all the materials. In the relationship between photographic blackening and exposure there is an initial portion of the curve, up to what may be called a threshold exposure, below which there is very little photographic response. Above the threshold the photographic response increases at a rate illustrated by the slope of the exposure/blackening curve, which is steepest for materials of the greatest photographic contrast. Finally, for large exposures, a form of saturation sets in and the degree of blackening approaches a maximum level, which again varies considerably between different materials.

These curves serve to illustrate the important distinction between photographic processes designed to produce a line print, as used in many drawing office and technical reproduction processes, and those in which a pictorial or half-tone result is required. In the case of line photography advantage can be taken of the sub-threshold region of the curve to ensure that the whites are truly unexposed, and that for the blacks one operates only at fairly high exposures on the curve. In this way initial slight fogging of the photographic emulsion can be rendered harmless in the final product. It is rarely possible to obtain significant benefit from this technique in the case of half-tone photography.

The saturation effect at the top of the curve should also be noted in our present context, as it represents a fogging level beyond which further exposures will produce no additional image.

2.3.2. Nuclear Radiation Sensitivity Curves.

The sensitivity of films and plates employed in the diverse branches of photographic recording varies over a very wide range, from the slow emulsions used in photo-mechanical processes to special X-ray emulsions. X-ray film emulsions are up to 10-30 times more sensitive to gamma radiation than are the ultra speed emulsions used in normal photographic recording. The density level (D) of blackening or fogging for an emulsion is given by

$$D = \log_{10} \frac{I_o}{I_t}$$

where I_o is the incident light and I_t the light transmitted through the film or plate. This density is variously quoted as net or gross density, depending upon whether or not the basic density of film base and unexposed emulsion has been subtracted. This correction usually amounts to less than 0.2 units on the density scale.

Because of the similarity between appropriately filtered X-radiation and gamma radiation, much of the work done in connection with the investigation of the sensitivity of emulsions to X-rays can be used as basic data in the examination of our present problem. There remain, however, certain differences in the effects, and it is therefore stated in each case whether the results given have been obtained with X-rays or with gamma radiation, and an indication is given of the mean energy of the radiation concerned.

According to Reference (1) the response of film to X- and gamma radiation is sensibly flat from high energies down to about 0.5 Mev. It then begins to rise until at about 70 Kev it may be some 10 or 20 times that at 1 Mev. Below 70 Kev it begins to fall off again and reaches the 1 Mev level again at about 40 Kev. This excessive response at low energies can be corrected by the use of a filter to attenuate the softer radiations, and with a thickness of 1 mm of tin or cadmium the response can be brought within about ± 10% over a range from several Mev down to about 60 Kev, after which is virtually a cut-off.

Reference (1) "Radiation Hazards and Protection" Barnes and Taylor (Newnes, 1958).

2.3.3. Results of X-ray tests.

Figures 2 and 3 (derived from Reference 1) indicate the gross fog in terms of density for a range of photo-sensitive emulsions including ultra fast, medium and slow process emulsions. Many films and plates will no doubt lie between the fast and slow types, but the curves would give some basis for evaluating the range of likely fog levels. The X-ray source used in these tests was a resonant transformer X-ray machine giving "hard" radiation, of approximately 1 Mev. These results should therefore be reasonably applicable to exposures to prompt gamma radiation from an atomic burst. The emulsions in these tests were exposed in cardboard cassettes, corresponding to normal packing. The emulsions were developed with an X-ray developer for five minutes at 68°F. This gives the maximum blackening which may be expected from other developers.

In a second set of tests (References 2 and 3) the results of which are given in Figures 4-9, the X-radiation used was adjusted to an effective energy of 96 Kev. This energy was chosen since, in general, record films are exposed in shielded positions and this leads to considerable scattering and "softening" of the original gamma radiation.

Some further measurements with 96 Kev X-rays on six types of R.A.F. film, and Kodak Plus X as control, are reported in Reference (4), (together with results of 1.25 Mev gamma irradiation of the same film types). R.A.F. development procedures were used in this investigation, the results of which are shown in Figures 13-19.

It must be emphasised that in addition to the type and energy of radiation, development procedure also will affect the form of the dose/density curve obtained. This is exemplified in Figure 20, which shows curves obtained with Plus X film under different development conditions, (Reference 5).

References (1) Corney G.M. and Cleane H.M.
Sensitivity to million-volt X-rays of several Kodak amateur and commercial photographic films. Laboratory Report No. 9591, November 18th, 1952.

(2) A.W.R.E. Report 0-33/57.
Effect of Gamma rays on record film, Interim Report No. 1. (Official use only).

(3) A.W.R.E. Report 0-4/58.
Effect of Gamma rays on record film, Interim Report No. 2 (Official use only).

(4) D.A.W. Plans Note No. 16.
"Military Air Photography and Nuclear Weapons". (Secret).

(5) R.L. Cater, A.W.R.E. Report - to be published.

2.3.4. Results of Tests with Gamma Radiation.

In an American Study reported at Reference (1), prompt radiation was simulated and figures quoted for HRHS Ortho, Tri-X, Eastman Colour positive and Eastman Colour negative films. Table 1 below indicates the approximate gamma ray exposures from Ir 192 and Co 60 (approximately 400 Kev to 1.3 Mev) required to produce a density of 0.5 above fog level, on development for five minutes at 68°F with ID - 19 developer.

TABLE 1

Film Type	Gamma dose (roentgens)
Industrial A X-ray film	0.5
Red Seal X-ray film	0.5
Industrial B X-ray film	1.0
" C " "	4.0
" F " " (fine grain high contrast)	6.0
Industrial G X-ray film (high sensitivity)	0.25
H.P.3 film	3.5
Hyperchromatic film	1.5
Bromide (normal)	26.0
	(Ir 192, normal development)

Some information on the sensitivity of a wide range of U.S. films to gamma radiation is given in Reference (2) and reproduced here in Figure 12. Table 2, also quoted from Reference (2), gives the results of measurements made in 1957 at Operation Plumbbob of radiation effects on several types of oscillographic recording paper.

Table 2

Radiation Effects on Recording Paper

Radiation Dose (Roentgens)	Effects				
	Line Writ 3 (L)	Visicorder (V)	K 809 (K)	K 1127 (K)	K 1112 (M)
0	A	A	A	A	A
0.1	A	A	A	A	A
0.5	A	A	A	A	A
1	A	A	A	A	A
5	A	A	A	A	A
10	B	A	A	A	A
30	B	A	A	B	A
50	B	A	NG	B	A
70	B	A	NG	B	A
100	B	A	NG	C	A
150	C	A	NG	C	A
200	NG	A	NG	NG	A
300	NG	A	NG	NG	-
500	NG	A	NG	NG	-
1,000	NG	A	NG	NG	NG

A = No fogging.
B = Slight fogging, fair records obtainable.
C = Medium Fogging, poor records obtainable.
NG = Dense fogging, no records obtainable.
- = No Data.

Figures 13-19, quoted from Reference (3) are dose/density curves obtained by exposing six types of R.A.F. film, and Kodak Plus X as control, to radiations from Co 60 (1.1-1.3 Mev), and using R.A.F. development procedures.

References (1) Edgerton, Germeshausen, and Grier Inc. Report No. 1068 (Unclassified)

(2) "Measuring Military Effects of Nuclear Weapons" compiled by Stanford Research Institute for A.F.S.W.P. December, 1958. (Official Use Only).
Chapter 11 - Photography - of this reference quotes information from Wyckoff W.W. "Sensitivity of Films to Gamma Radiation". Edgerton, Germeshausen, and Grier Inc. Report 1361, Revised October 1955, (Unclassified).

(3) D.A.W. Plans Note 16, "Military Air Photography and Nuclear Weapons" (Secret).

2.3.5. Results of Beta Tests. The figures in Table 1 below have been obtained using a thallium 204 source, the beta rays having a maximum energy of 770 Kev. These figures are regarded as being less reliable than those for gamma rays. The conditions of development and degree of fogging are as previously given for Table 1 of Section 2.3.4 above.

Table 1

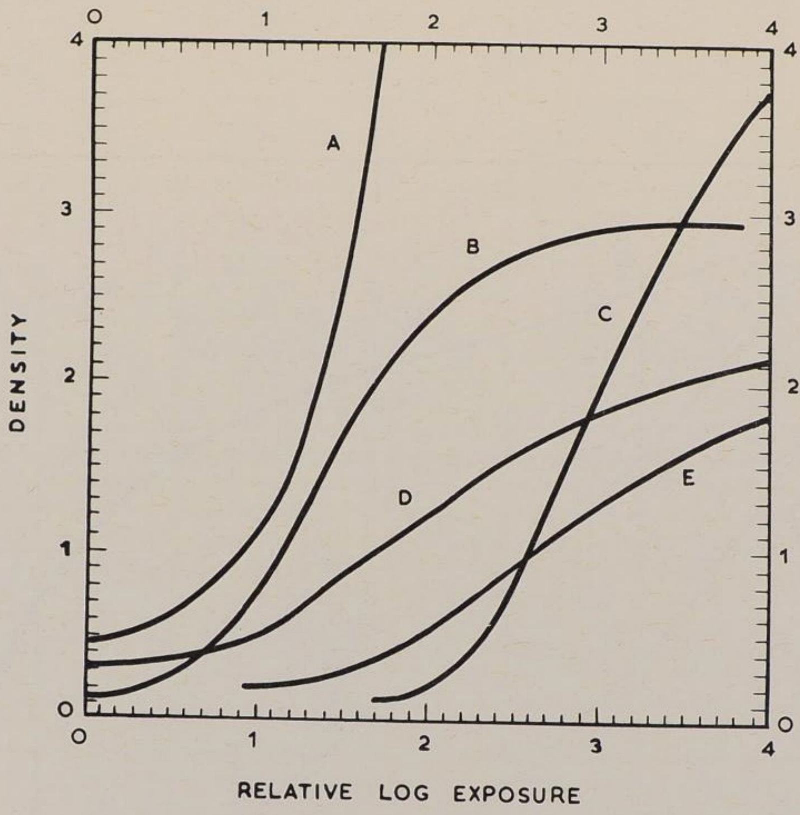
Film Type	Electrons/cm^2 for density 0.5
Infex	1.5×10^5
Industrial A & B	2×10^5
Standard X-ray	3.5×10^5
5G 91 (recording)	1×10^6
Hyperchromatic	0.9×10^5
H.P.3	1.3×10^6
F.P.3	3×10^6

Measurement of beta dose using film emulsions is reported in Reference (1), which gives details of the use of modified and unmodified FM 1 film for the measurement of small doses of beta radiation as a function of beta ray energy. Figure 10 shows the response of the film in its wrapping as supplied by Ilfords, and Figure 11 the response of the film after half the emulsion has been stripped off.

Reference (1) A.W.R.E. Report O-36/56 "The Measurement of Beta - Dose using Film Emulsions". (O.U.O.).

2.3.6. Response to Alpha Radiation. No data are presented on the response of photographic emulsions to alpha radiation, as this radiation could only arise from the fissile material of the bomb itself, and even if this were deposited as fallout the radiation would be of extremely short range. It would thus merely add a small amount to the spotting caused by beta radiation from fission particles in the fallout.

2.3.7. Neutron Irradiation. The sensitivity of normal film emulsions to neutrons is quite low, about one-hundredth of that to X-rays in terms of equal biological dose. However, as pointed out in Section 2.2.1 above, there are various circumstances in which neutrons give rise to secondary radiations, which themselves may have significant effects on film emulsions. For example if a cadmium filter is used the response to thermal neutrons is greatly increased because of the capture radiation produced, and about the same sensitivity is obtained for X- and gamma rays and thermal neutrons. (Reference Barnes and Taylor - Radiation Hazards and Protection).



A = 'KODIREX' X-RAY FILM

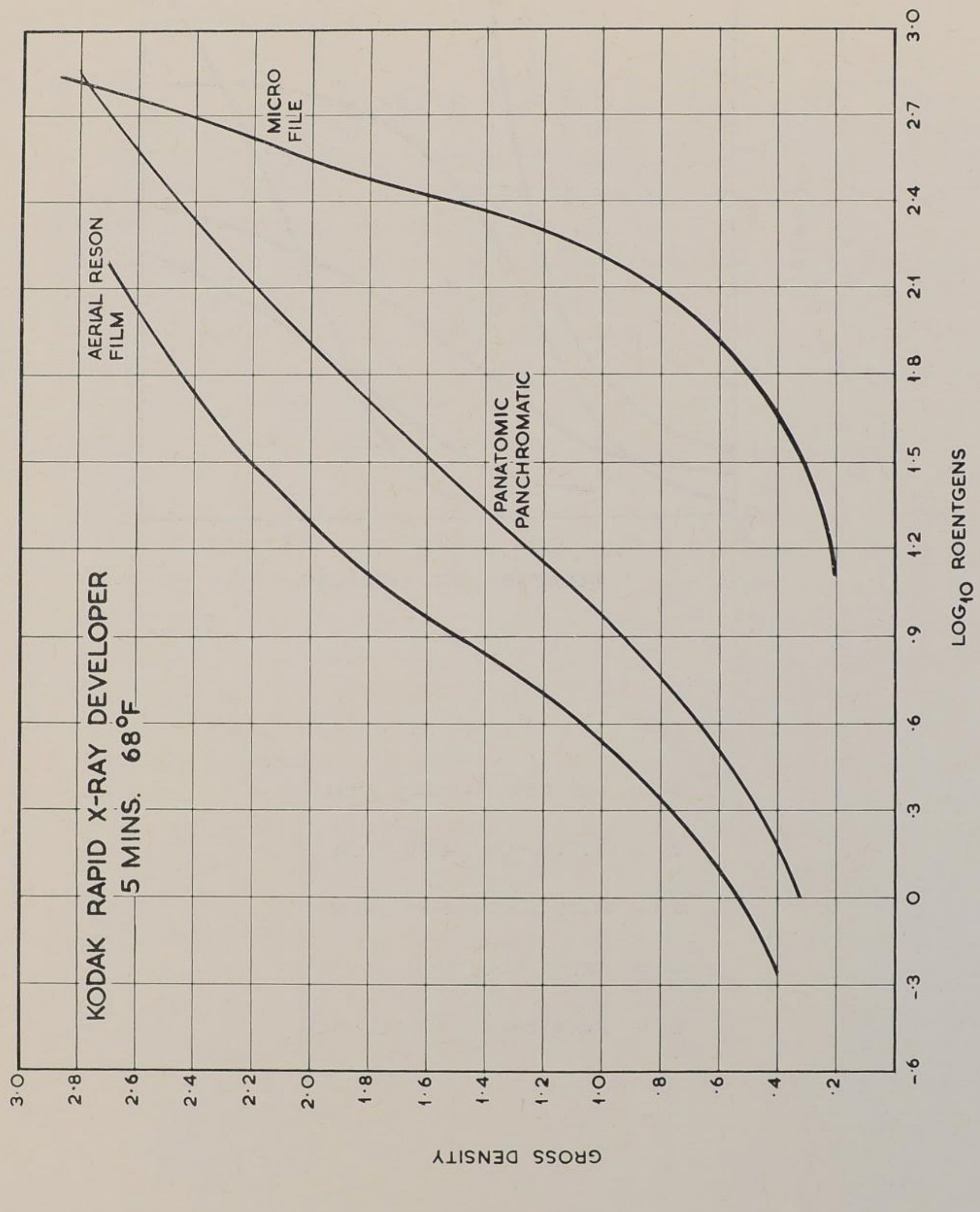
B = SUPER-XX AERO FILM

C = R.20 RECORDING FILM

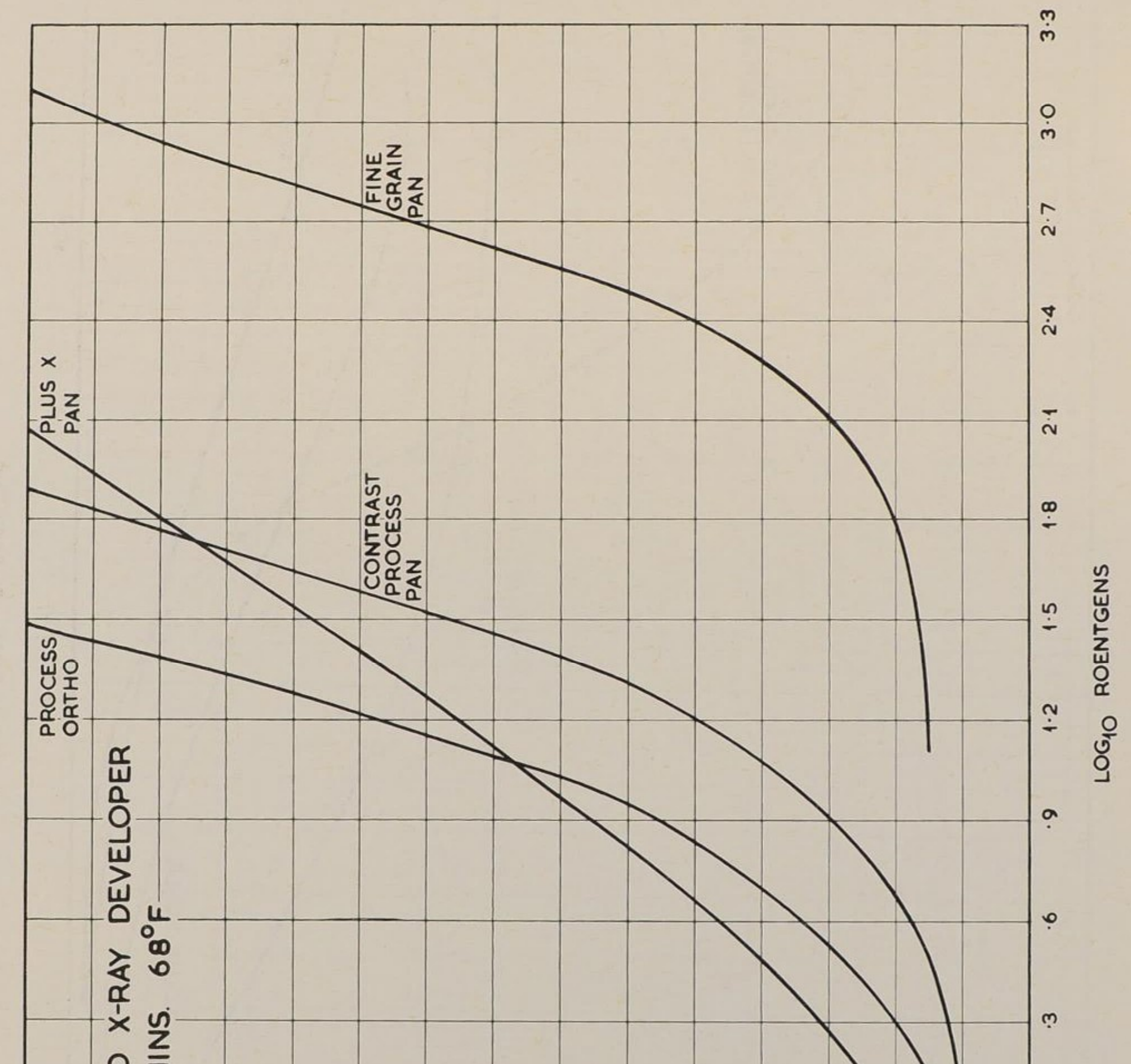
D = TRI-X ROLL FILM

E = PANATOMIC-X ROLL FILM

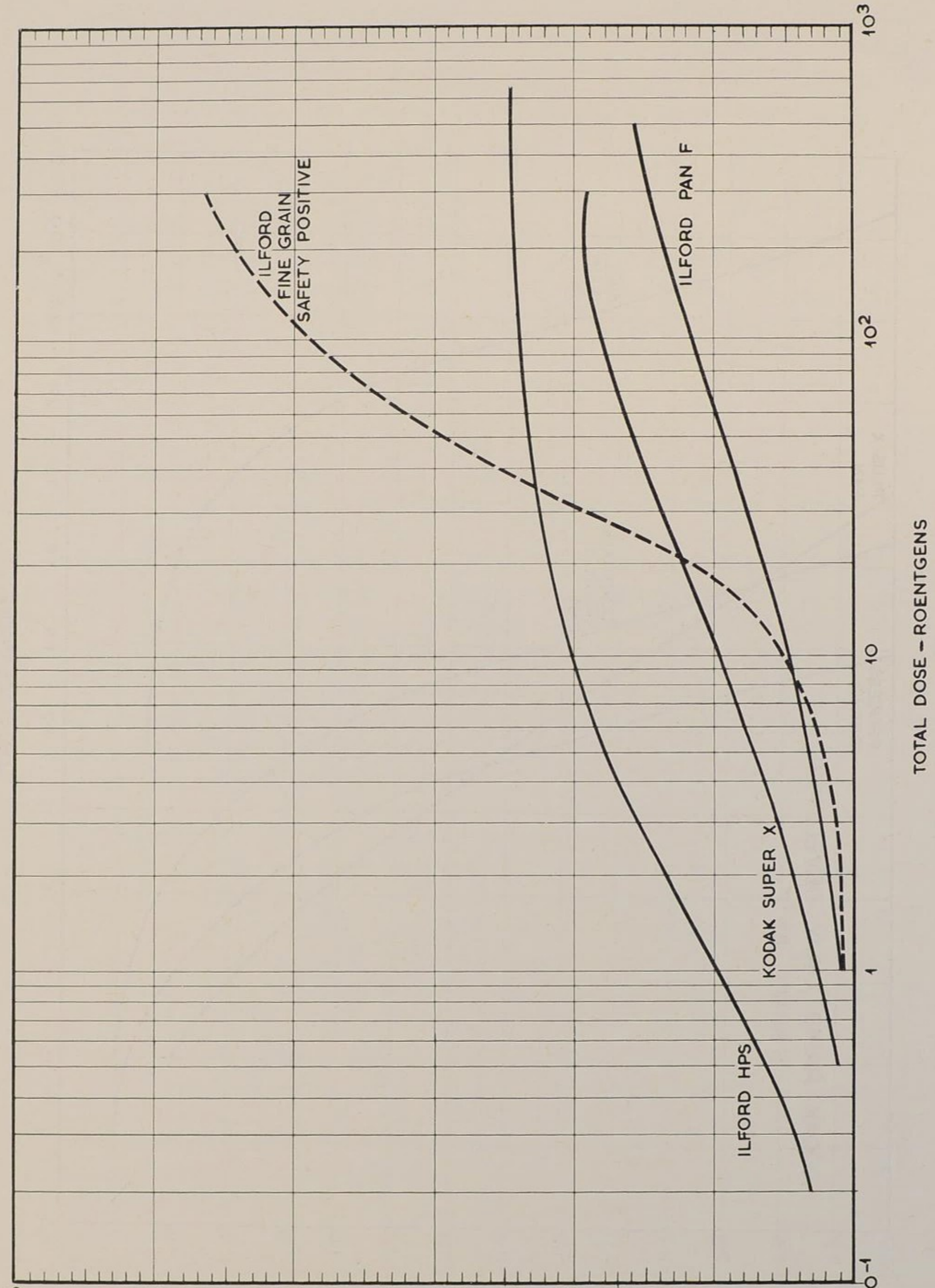
CHARACTERISTIC CURVES FOR VARIOUS KODAK FILMS



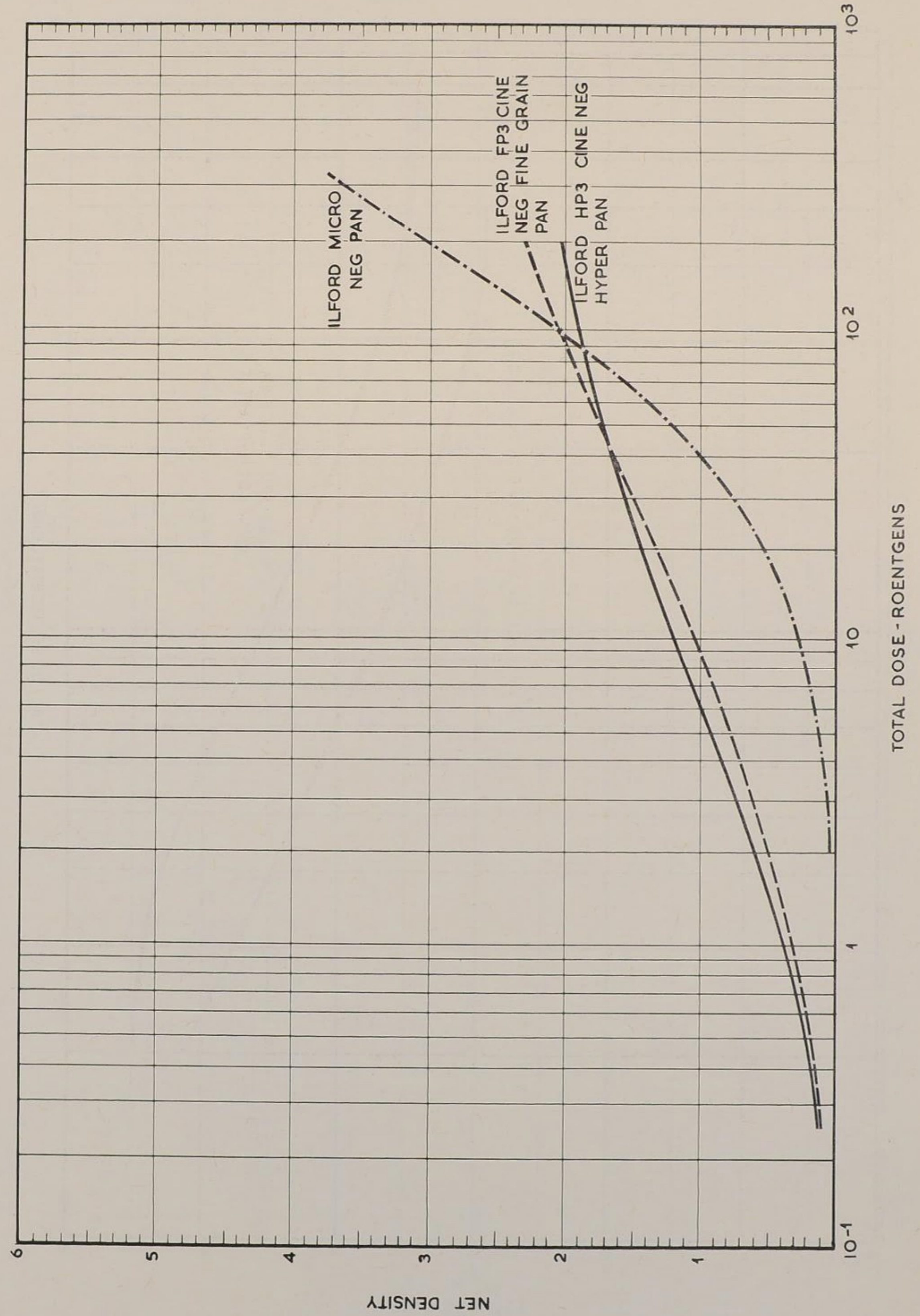
DOSE/DENSITY CURVES FOR VARIOUS KODAK FILMS
(1 MEV X-RAYS)



DOSE/DENSITY CURVES FOR VARIOUS KODAK FILMS
(1 MEV X-RAYS)



DOSE/DENSITY CURVES FOR VARIOUS FILMS
(96 KEV X-RAYS)



DOSE/DENSITY CURVES FOR VARIOUS FILMS
(96 KEV X-RAYS)

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SECTION 2·3
FIGURE 6

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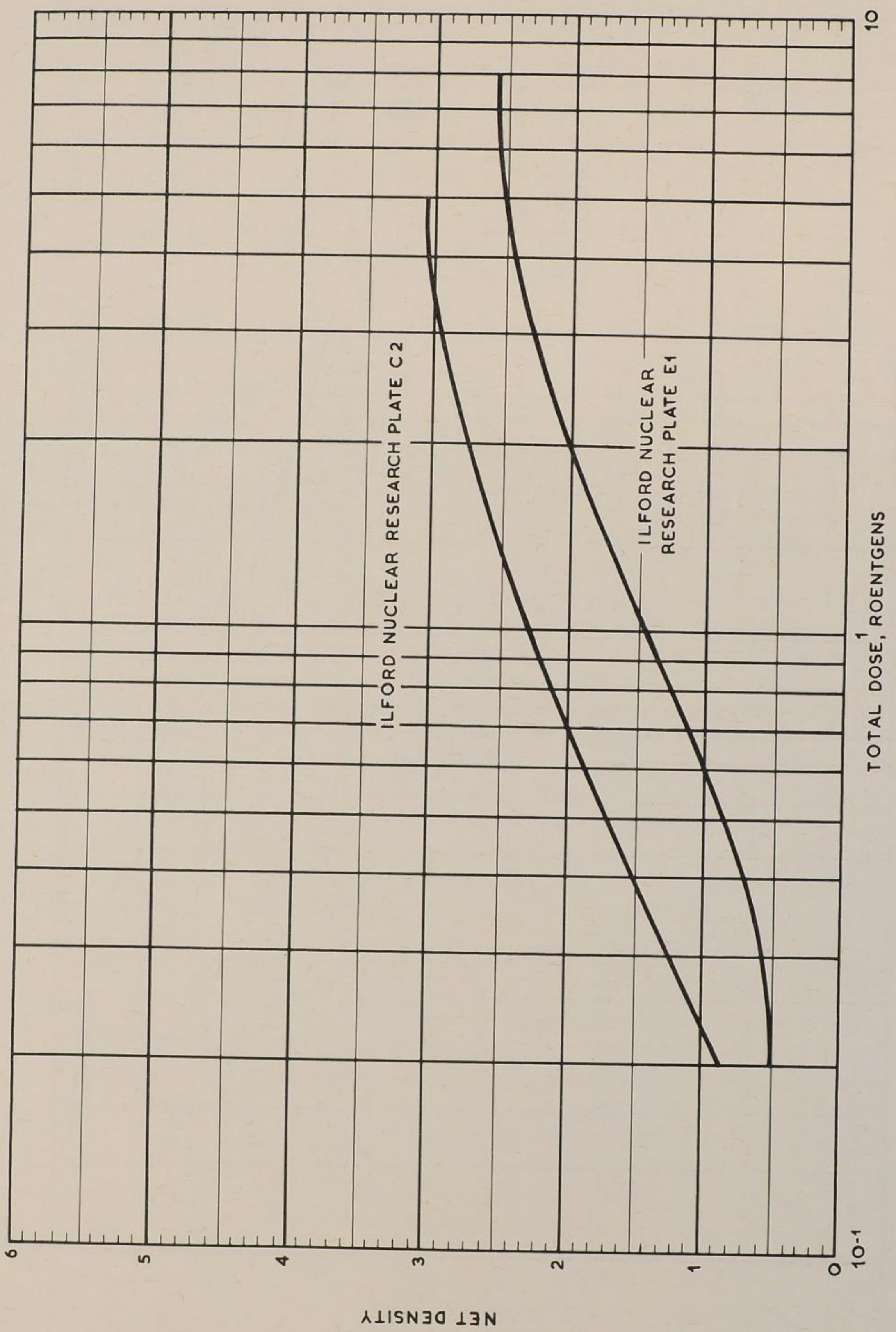

DOSE/DENSITY CURVES FOR VARIOUS FILMS
(96 KEV X-RAYS)

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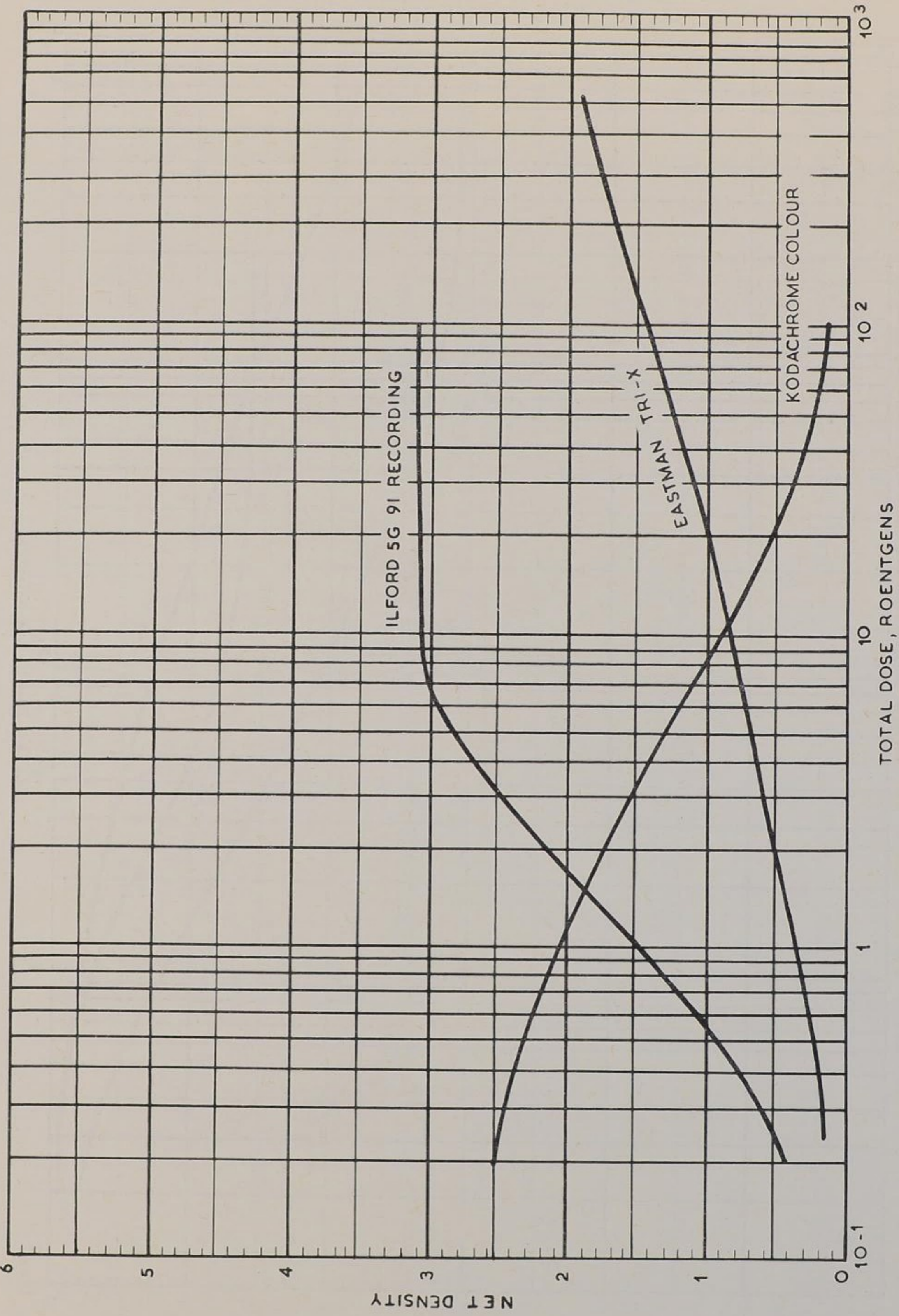
USE ONLY



DOSE/DENSITY CURVES FOR VARIOUS FILMS
(96 KEV X-RAYS)

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FIGURE 8

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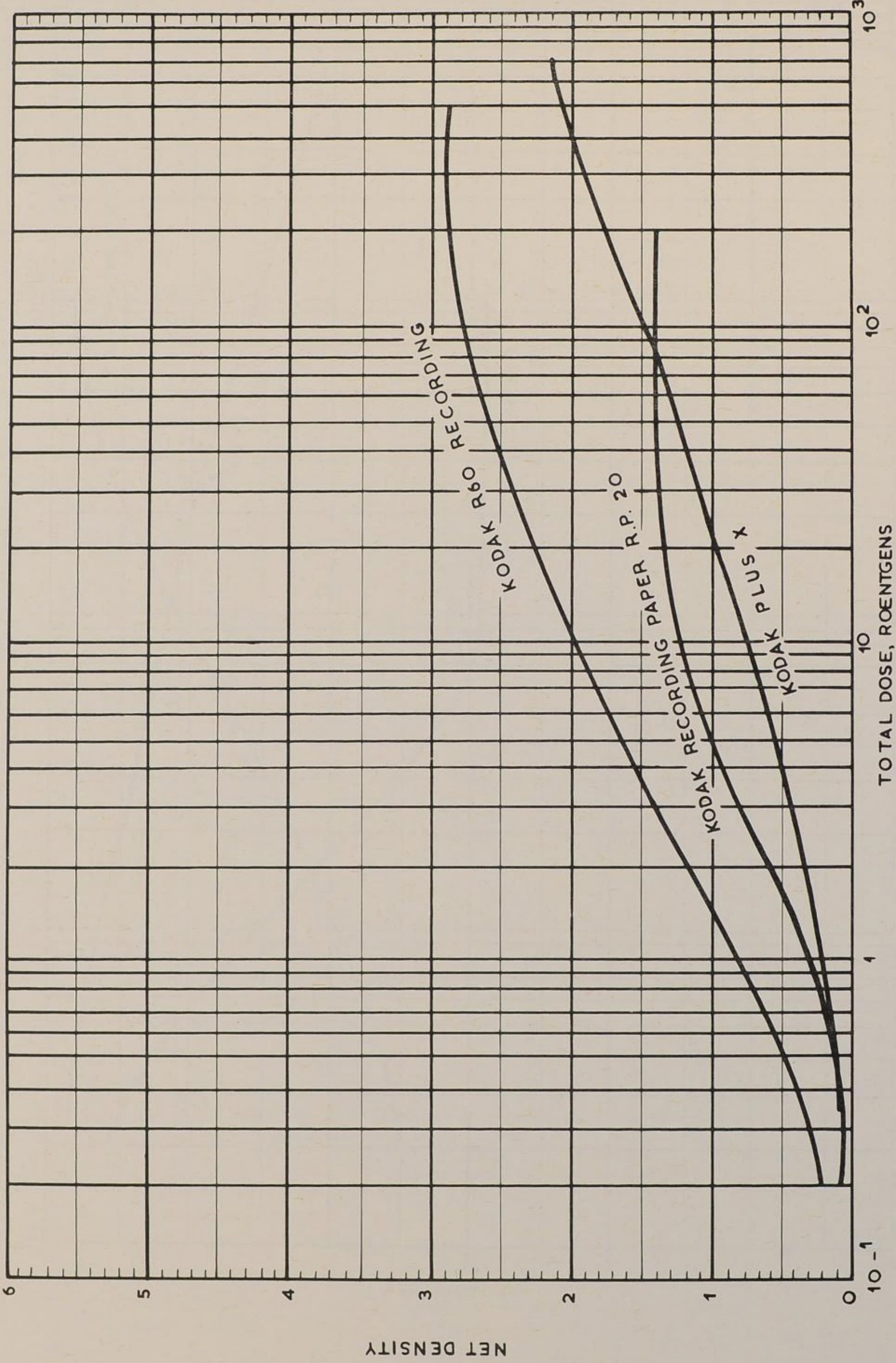

DOSE / DENSITY CURVES FOR VARIOUS FILMS
(96 KEV X-RAYS)

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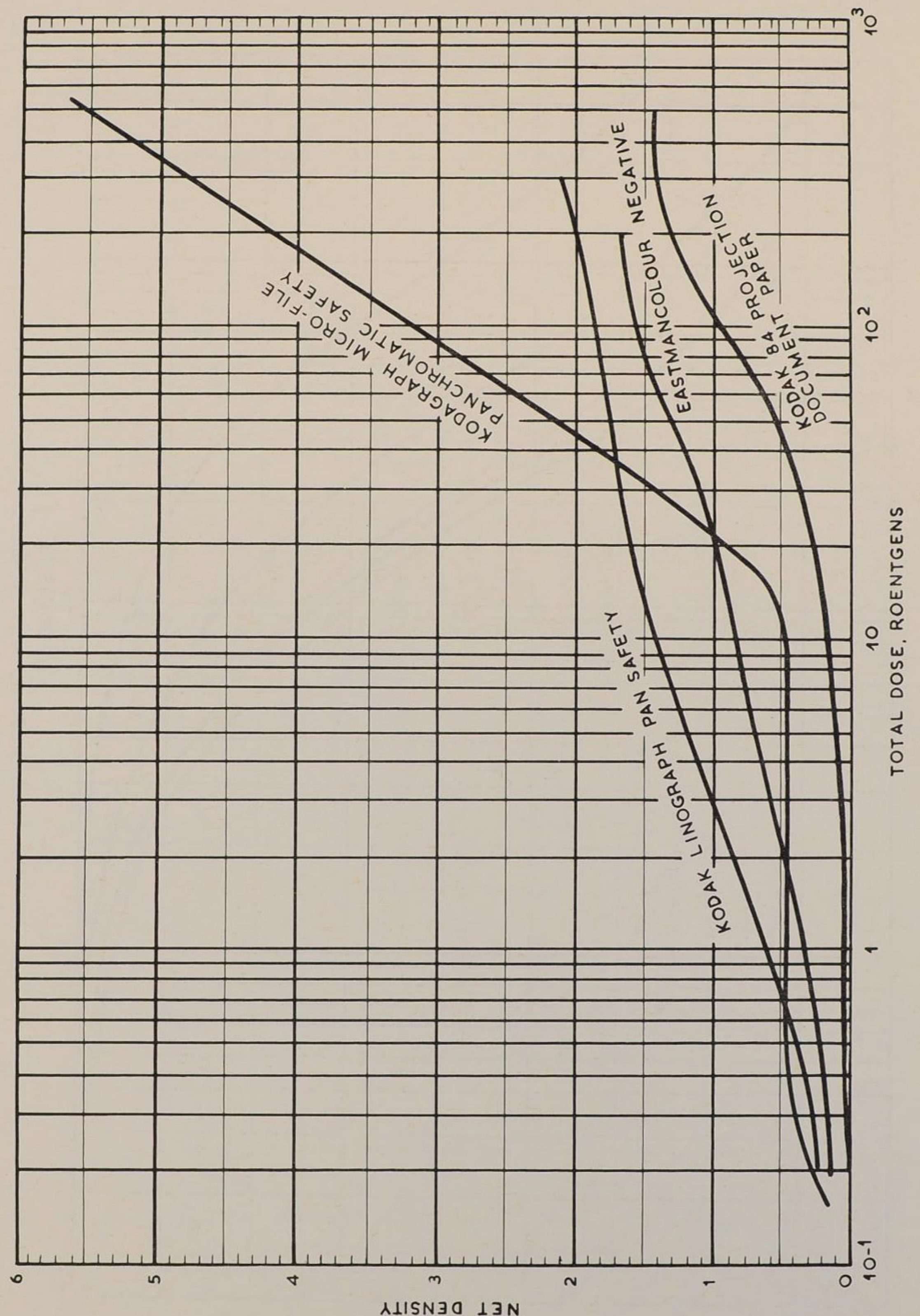
FIGURE 9



DOSE / DENSITY CURVES FOR VARIOUS FILMS
(96 KEV X-RAYS)

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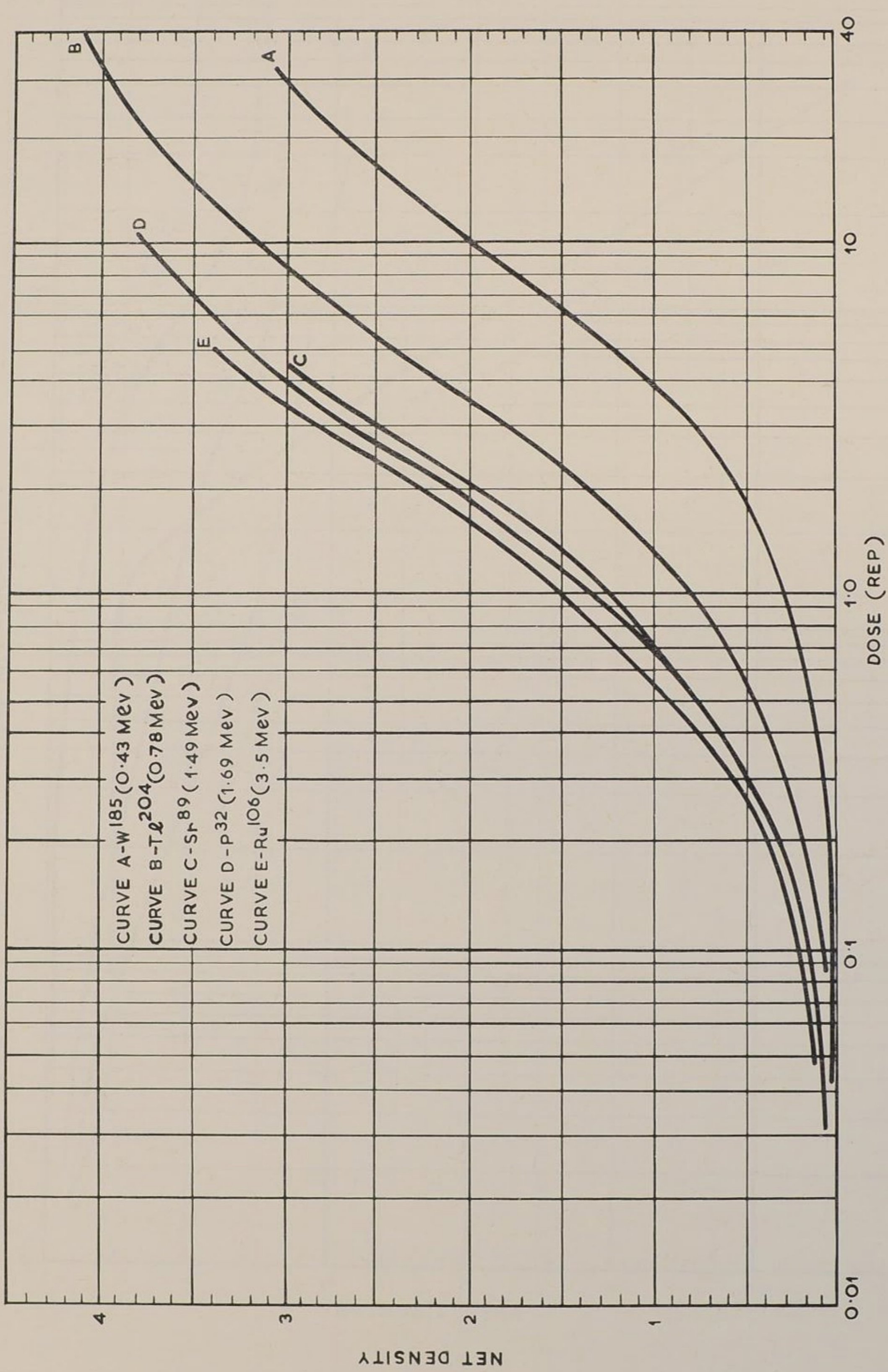

RESPONSE OF PMI FILM (IN ITS WRAPPING)
TO BETA RADIATION

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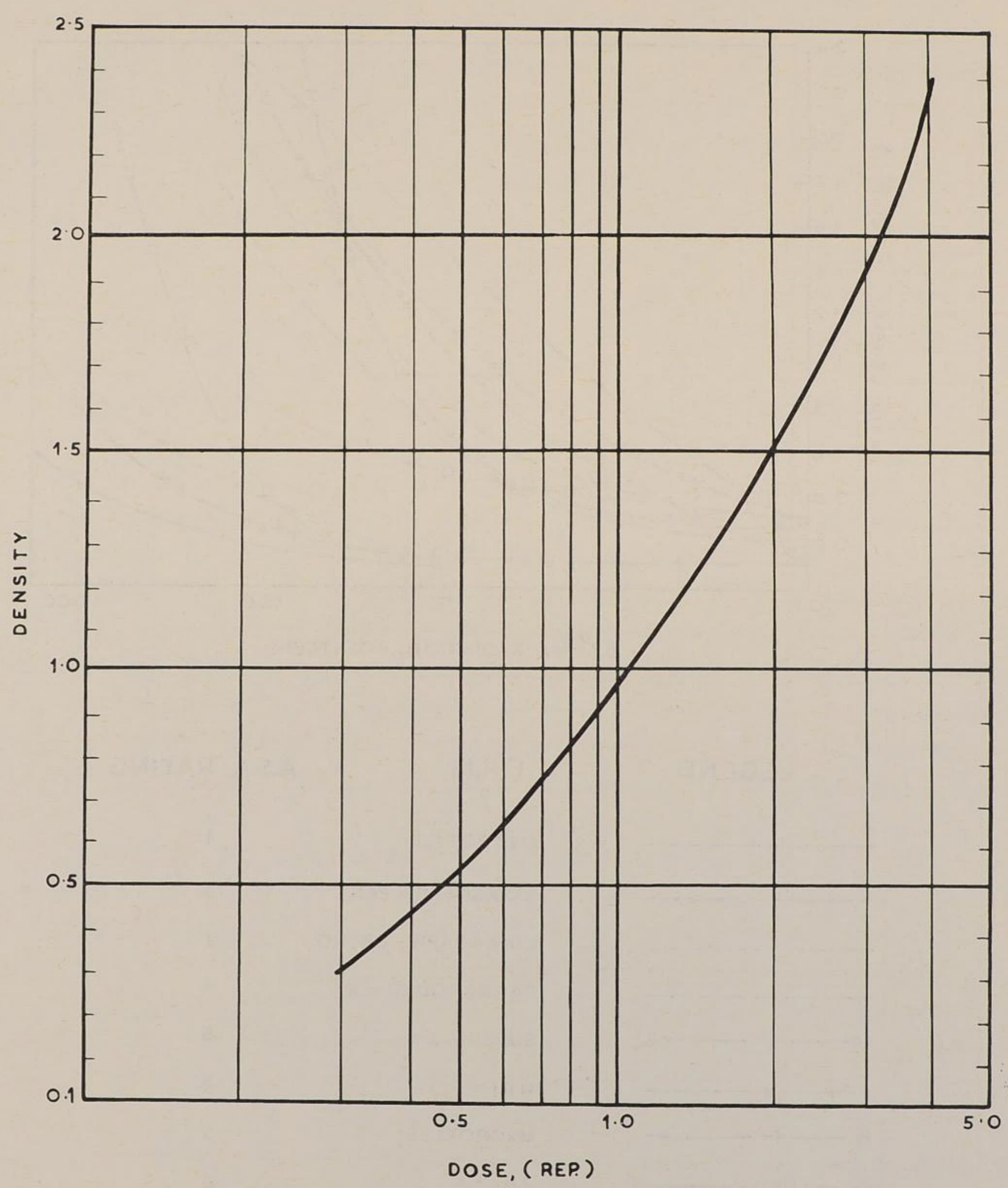
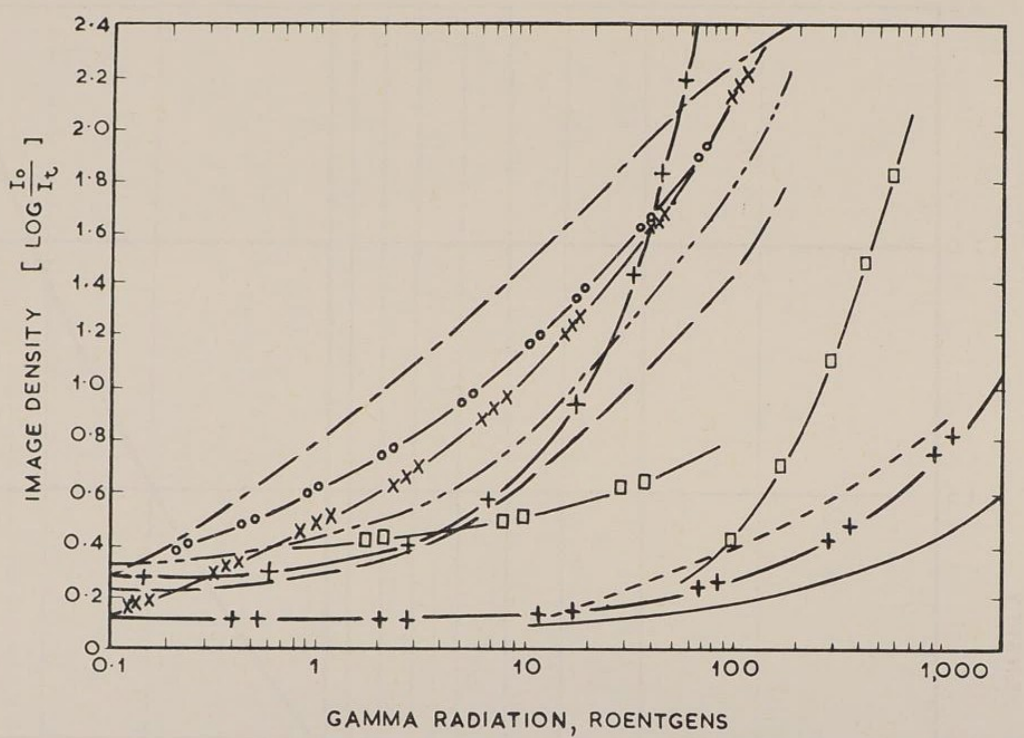


CALIBRATION CURVE FOR RESPONSE TO BETA RADIATION OF PMI FILM WITH HALF EMULSION STRIPPED OFF

OFFICIAL
USE ONLY



LEGEND	FILM	A.S.A. RATING
————————	MICROFILE	1
- ———— - ———— -	LINAGRAPH - PAN	2
———— - - ———— - -	LINAGRAPH - ORTHO	3
—— —— —— ——	BACKGROUND - X	4
oo———— oo ———— oo	SUPER - X X	5
+ ———— + ———— +	HRHS	6
++ ———— ++ ———— ++	MICROFILE	7
———— XXX ————	TRI - X	8
□ ———— □ ———— □	ECP	9
———— □ □ ————	ECN	10
- - - - - - - - - - -	LINAGRAPH PAPER	11

SENSITIVITY OF VARIOUS U.S. FILMS
TO GAMMA RADIATION

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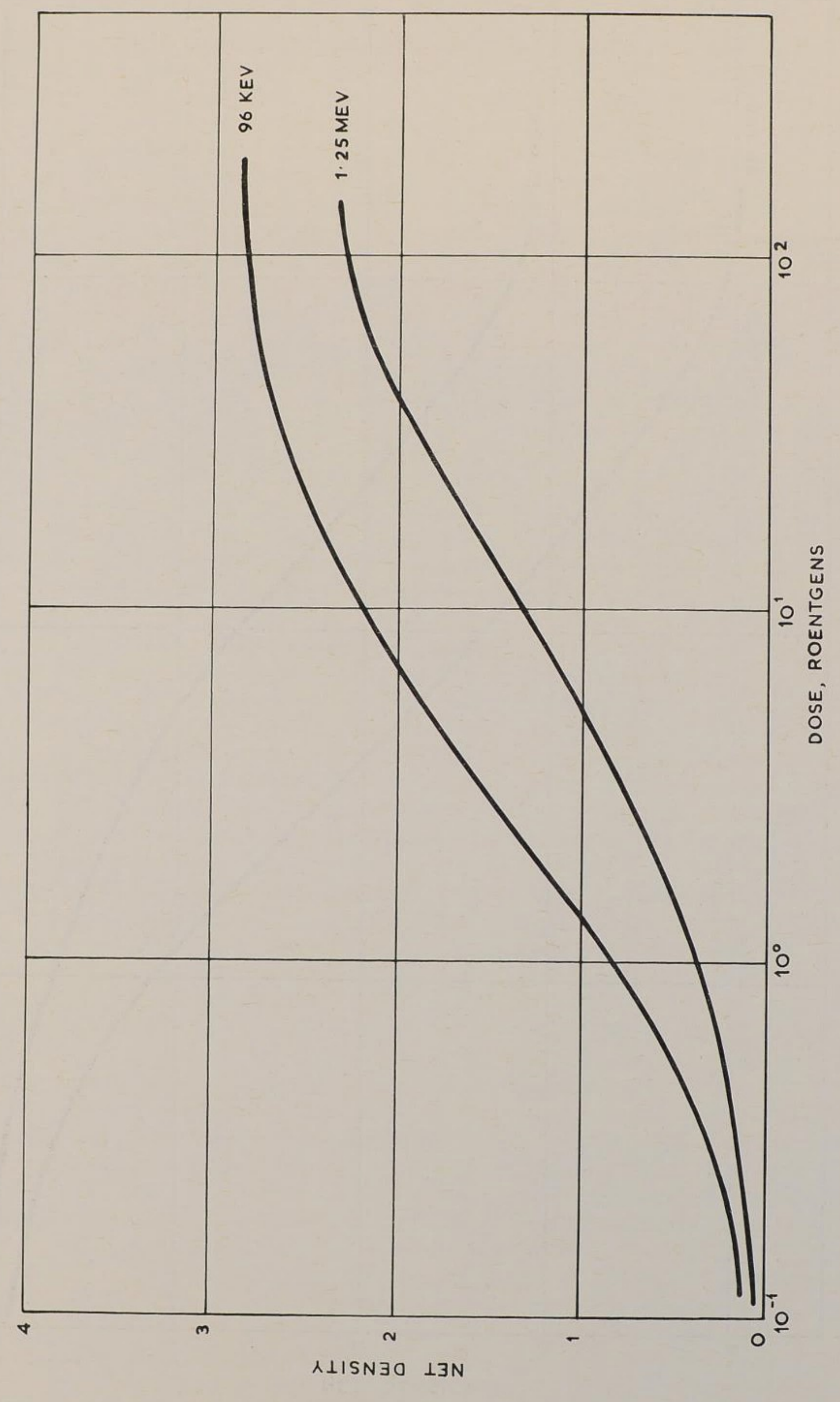
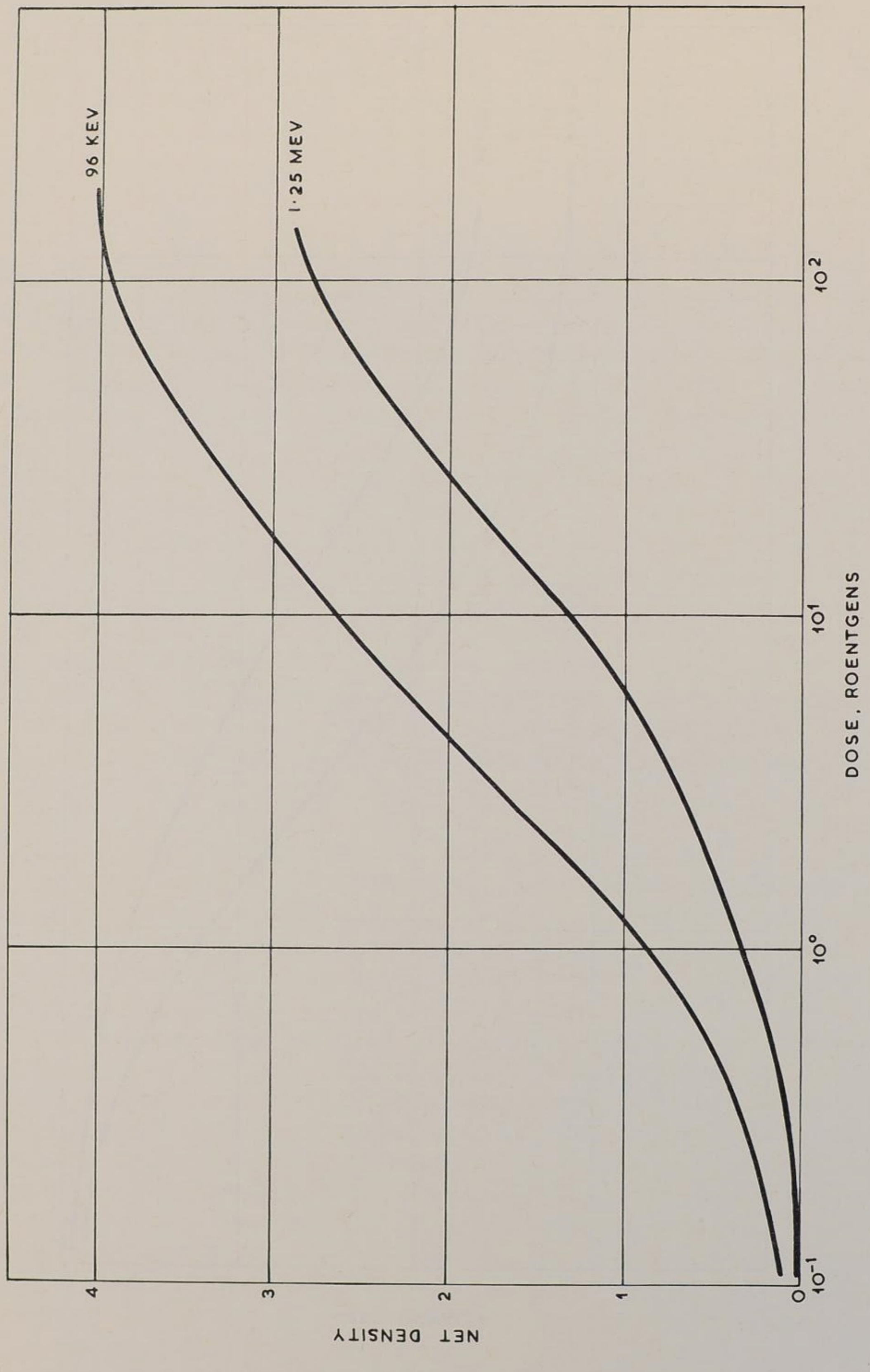


R.A.F. FILM CLASS L. HIGH ALTITUDE DAY RECONNAISSANCE AND SURVEY. KODAK

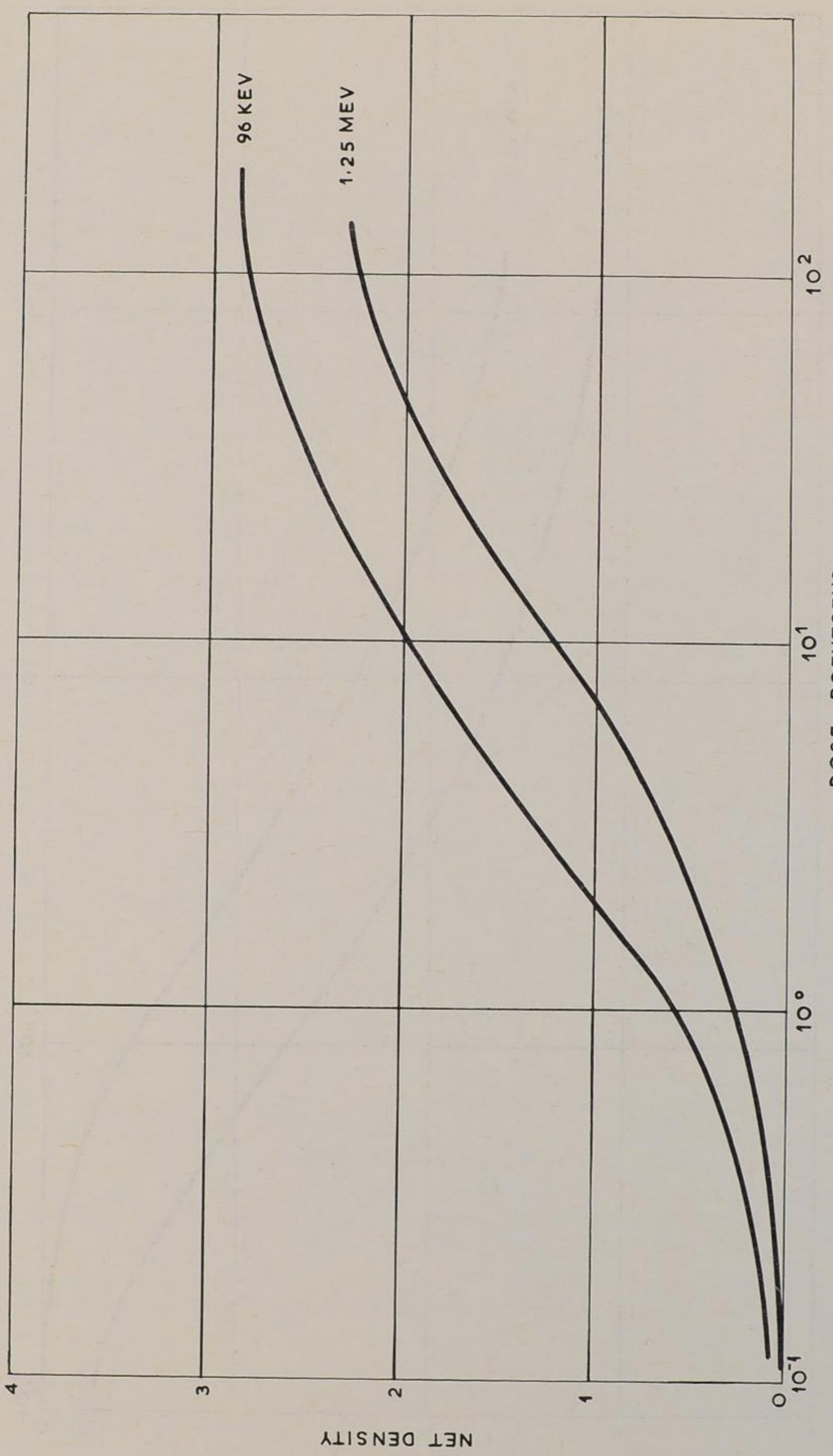
CONFIDENTIAL

D1/57
SEPT. 1959



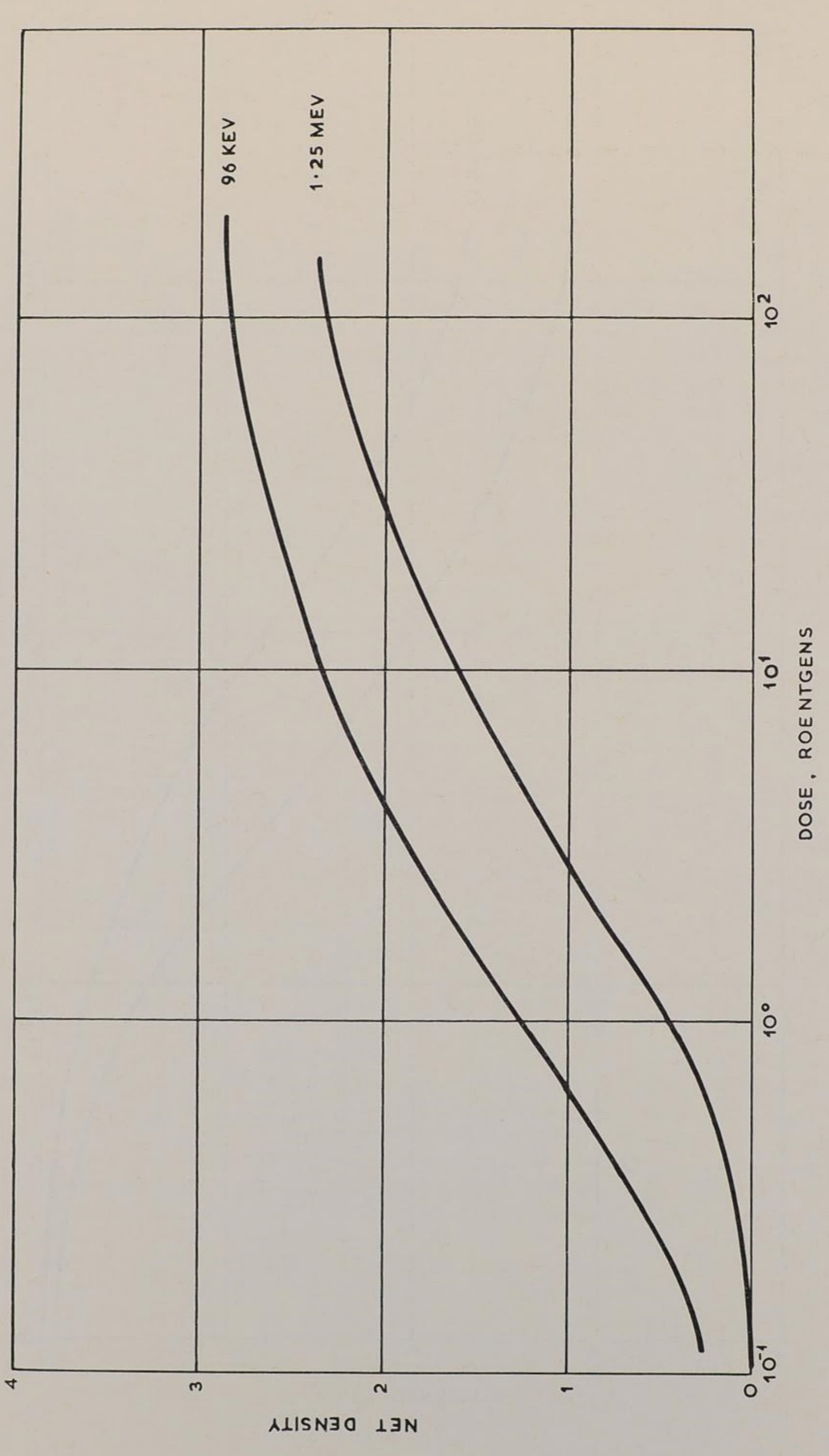
R.A.F. FILM CLASS L. HIGH ALTITUDE DAY RECONNAISSANCE AND SURVEY. ILFORD

CONFIDENTIAL



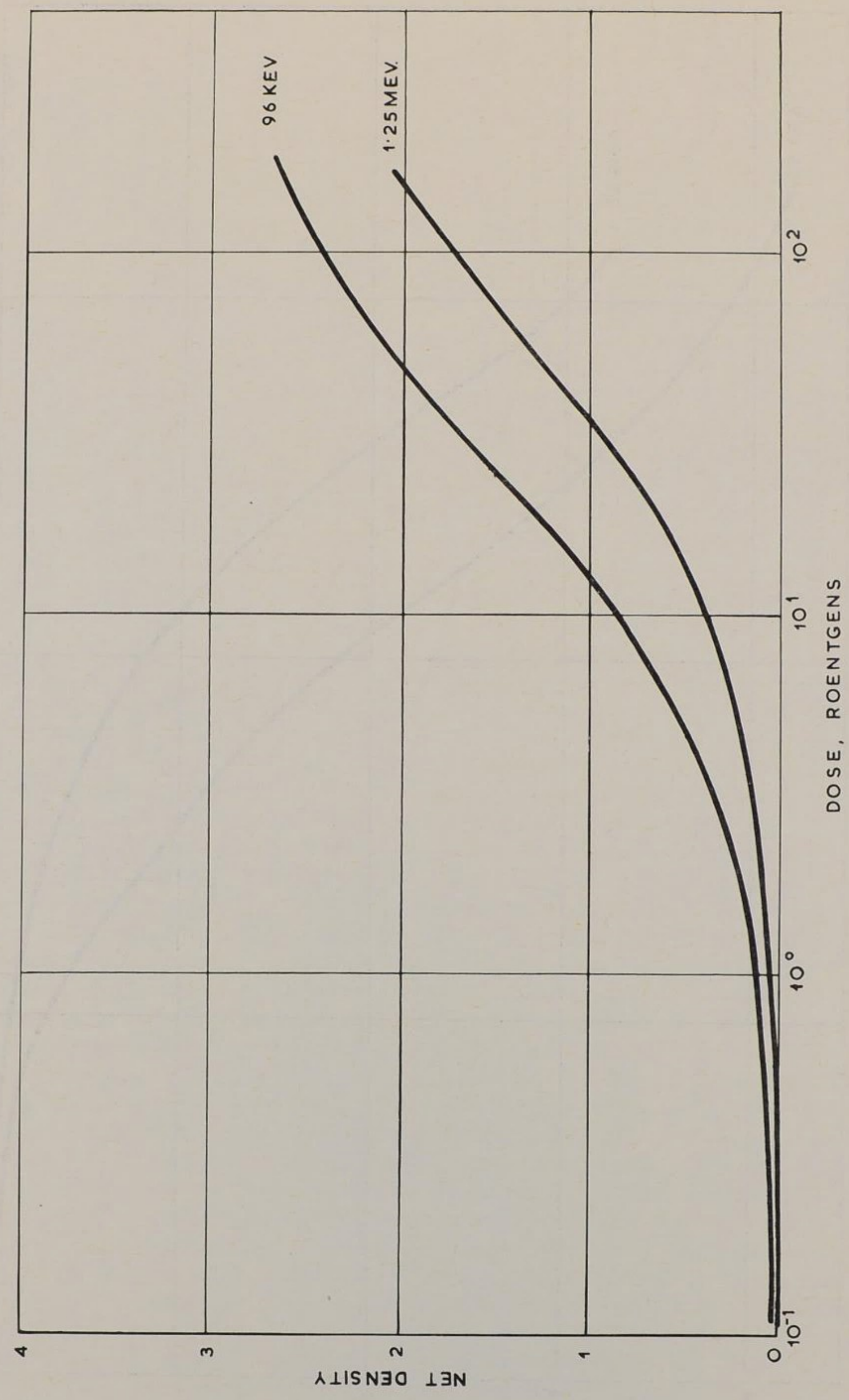
R.A.F. FILM CLASS L. 3. LOW
ALTITUDE DAY RECONNAISSANCE. ILFORD

CONFIDENTIAL



R.A.F. FILM CLASS N. HIGH AND LOW ALTITUDE NIGHT RECONNAISSANCE. ILFORD

CONFIDENTIAL



R.A.F. FILM CLASS C. GUN CAMERA AND HIGH ALTITUDE HIGH RESOLUTION RECONNAISSANCE AND SURVEY. KODAK

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CHAPTER 2
SECTION 2.3
FIGURE 18

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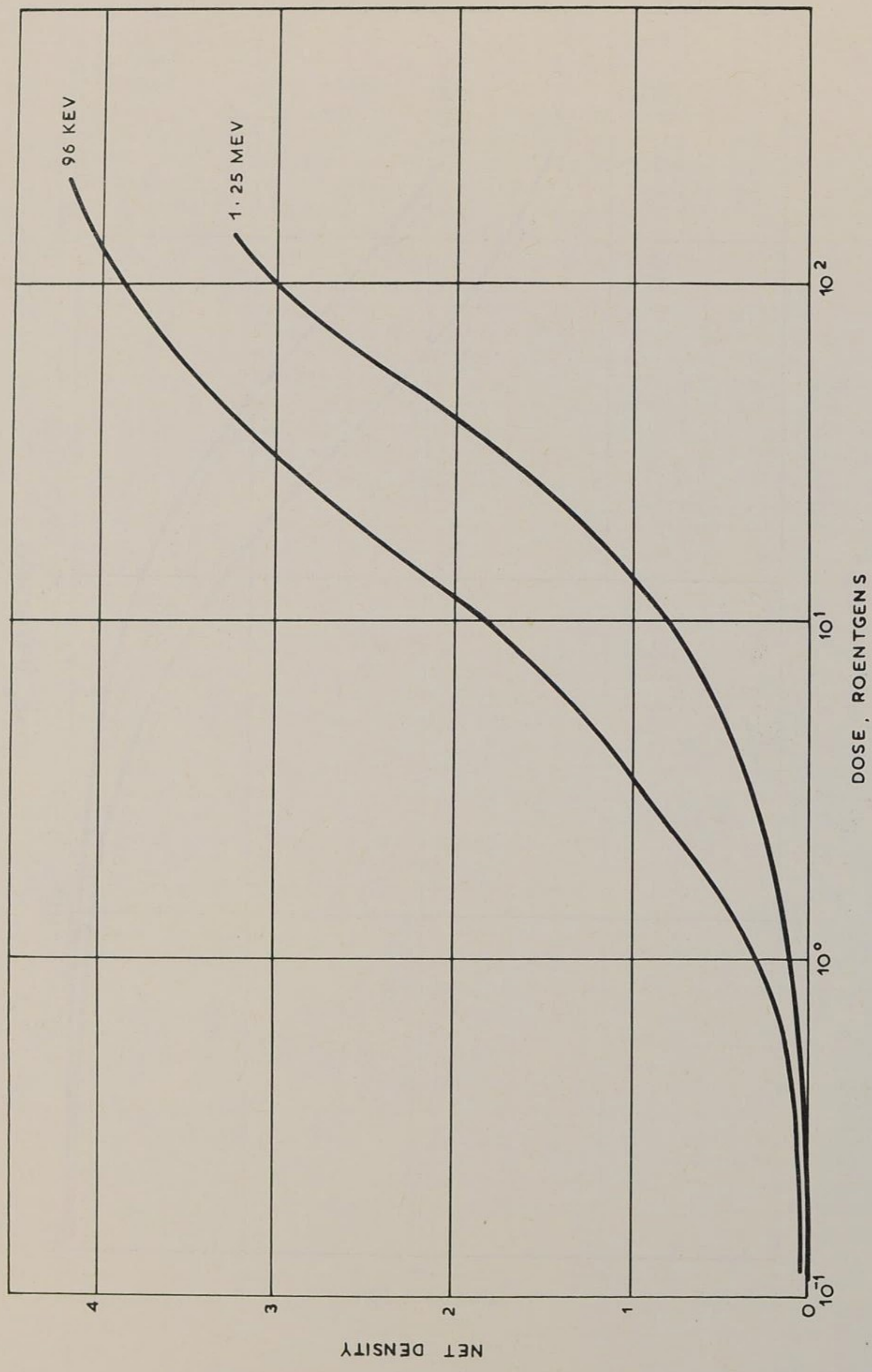
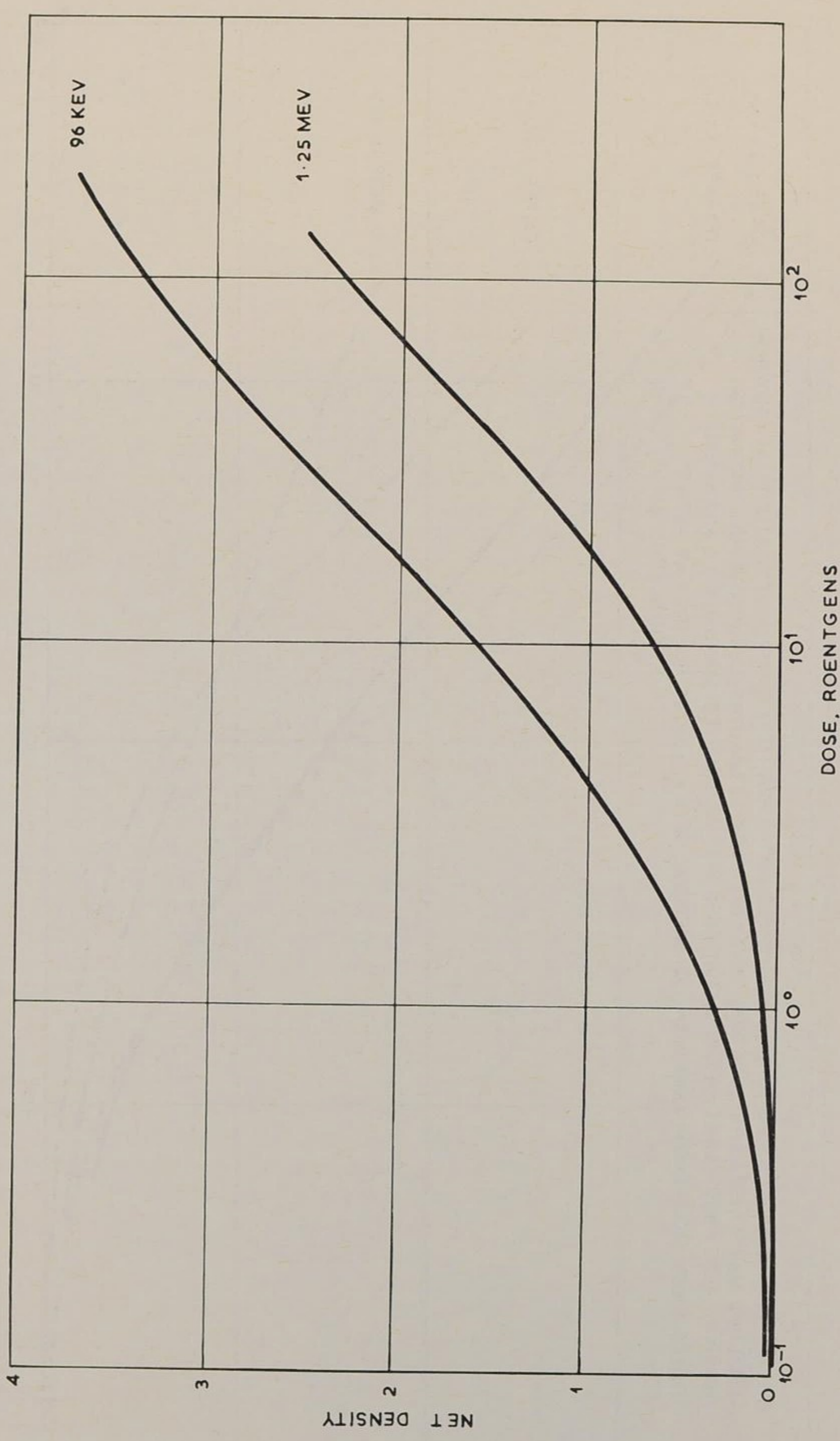


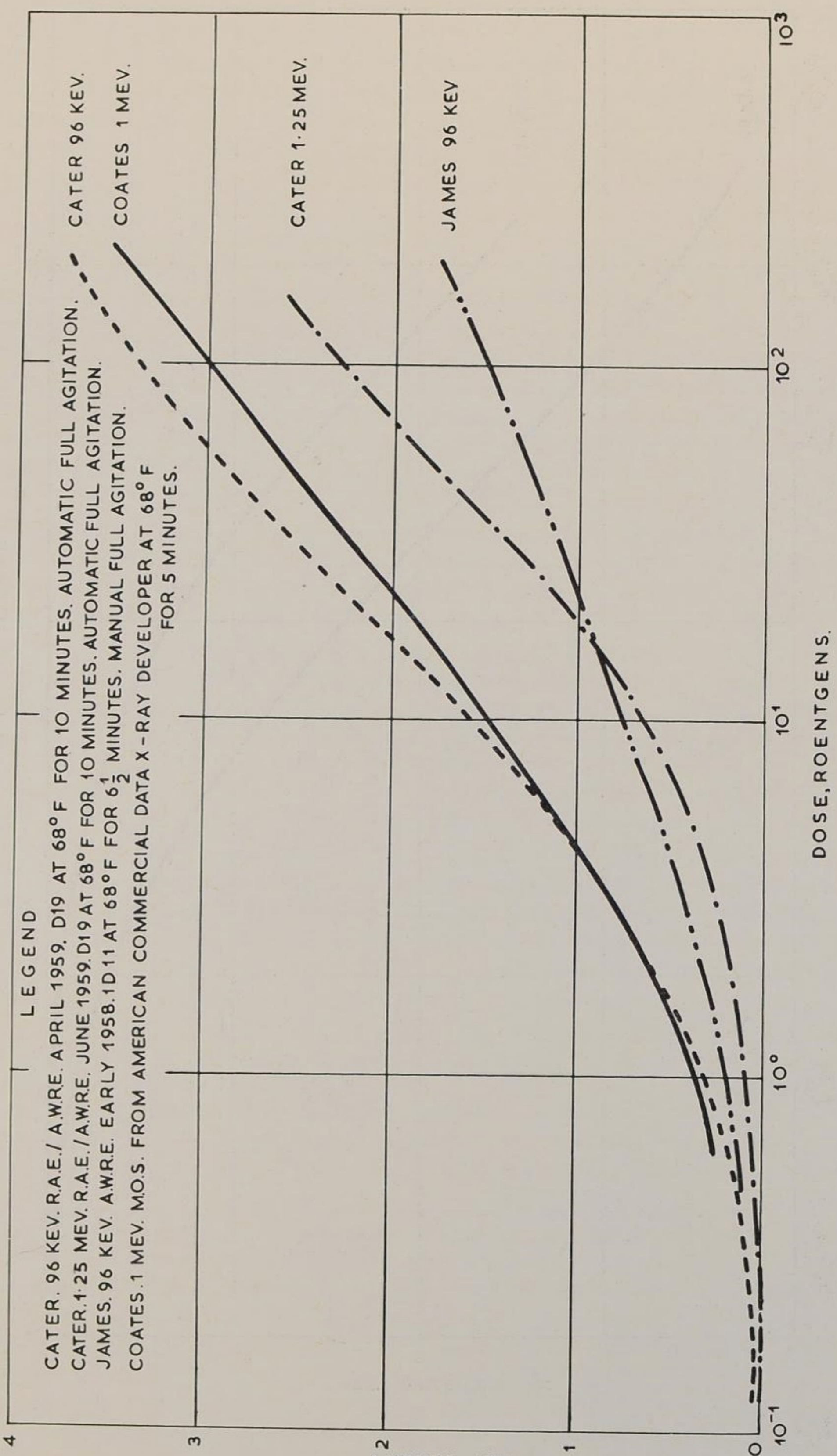
CLASS C. GUN CAMERA AND HIGH ALTITUDE HIGH RESOLUTION RECONNAISSANCE AND SURVEY. ILFORD

CONFIDENTIAL


96 KEV
1·25 MEV
NET DENSITY
0
1
2
3
4
DOSE, ROENTGENS
10^{-1}
10^{0}
10^{1}
10^{2}

KODAK PLUS X

CONFIDENTIAL



COMPARATIVE CURVES FOR KODAK PLUS X FILM

CONFIDENTIAL

2.4. Tolerable Fog Levels for Various Purposes

The amount of background fog tolerable in a sensitive emulsion depends upon the purpose and method of use. The fundamental point is the density scale required from the original subject, and this in turn will depend upon the range of densities in the subject itself. The question of subject-density range will be dependent upon colour, texture and illumination. A subject which presents a measured density range of 0 - 0.3 would be unsatisfactory if recorded on a film fogged to a level of 0.3; on the other hand, a subject with a wider density range might be considered satisfactory depending upon the part of the density scale which is to contain information.

For example, a photograph made from the air from a considerable height, on a dull day and of a flat terrain, would have a relatively low contrast and would be quite unsatisfactory if recorded on an emulsion with even a low fog level of say 0.3 - 0.4. On the other hand, a high contrast subject, containing a strong highlight/shadow range, might satisfactorily record on a film with a relatively high fog density level, perhaps 0.7 - 1.0. As an extreme example, line-type subjects involving no half-tones might satisfactorily record with quite heavy background fogging, and a density of 1 - 1.8 might still be tolerable for recording a cathode ray tube trace in cases where there were no large variations of C.R.T. spot writing speed at important parts of the trace.

The above paragraphs consider only an overall even fogging. Spots of large or small diameter and of varying degrees of density may be experienced if fall-out particles come into contact with the emulsion. In such cases no general statement could be made of the degree of usefulness of the photographic emulsion, as the amount of interference with image detail would be the deciding factor. For example, in the case of photographs of a radar plan position indicator tube, it would be equivalent to an increase in noise level.

As a rough guide to orders of magnitude it is suggested that a fog level of 0.5 be considered the absolute maximum where half-tone reproduction is required, and a fog level of 1.5 the upper limit for line processes.

Permissible fogging levels for military air photography are discussed in Reference (1). In this reference operational tasks are divided into three broad classes as follows:-

Class 1 — Fine detail low contrast photography where maximum performance is needed. This could in time of war include most high altitude day or night photography where, for example, adverse lighting might have to be accepted and where fine detail or shadow measurements might be required for intelligence and similar purposes.

Class 2 — Low altitude and gun photography where a good general standard of photography is adequate. This covers the situation where the size of the image is in general sufficient to allow interpretation through a moderate amount of background fog.

Class 3 — Data recording. In such pictures there is often a high degree of redundancy and the lighting can in some circumstances be adjusted to reduce the effect of fogging.

The above classifications are clearly not absolute. Some high altitude work might fall into Class 2 and some low altitude work into Class 1. Air-to-air gun camera photographs might tend towards Class 3. Airborne-radar photographs of low resolution might be in Class 3, whereas high resolution radars might tend to Class 2.

Reference (1) assigns tentative fog levels to these three classes on the basis of advice received from various specialists who have had practical experience in this field. For a general fogging a net density of 0.4, 0.9 and 1.5 is taken for Classes 1, 2 and 3 respectively. Some modification might be made to these figures in a more refined treatment, but it is unlikely to affect significantly the tactical situation.

Reference (1) D.A.W. Plans Note No. 16.

"Military Air Photography and Nuclear Weapons" (Secret)

2.5. Routine Precautions

There are several ways in which risks of fogging may be minimised by techniques which really amount to "good housekeeping". Some of these techniques are briefly considered in the following paragraphs.

2.5.1. Water Supplies

The water used in the manufacture and in the subsequent processing of photographic emulsions is an obvious possible source of trouble if it has been contaminated by radio-active fall-out. This applies particularly where the sources of supply are from rivers or reservoirs. As fall-out is well filtered by the passage of water through quite small thicknesses of soil, underground water supplies are likely to be reasonably safe. Water stored in covered tanks would be protected from fall-out, and provided that no new intake is made, such water would be safe if piped directly to the laboratory. Water supplied by artesian wells, as commonly used by photographic manufacturers, is considered to be safe. In the event of filtration being required, it is considered that if water supplies are filtered so as to exclude particles larger than 2 microns in size any fogging will be of a negligible level (below 0.05).

2.5.2. Long-Term Storage of Photographic Materials

Photosensitive materials require protection from prompt radiation, and also from the effects of radioactive fall-out, by being stored inside adequate shielding. The requirements for this shielding are considerably more severe than would be the case for personnel, both on account of the greater sensitivity of photographic emulsions and on account of the generally longer periods of exposure involved. Underground storage would have to be some tens of feet below surface level in order to give adequate protection. Part VII of this Manual should be consulted for details of shield thicknesses for given attenuation factors.

Such underground storage would require adequate sealing against the ingress of radioactive dust. It has been suggested that this should be effected by pressurising the chambers to a small amount above normal atmospheric pressure, care being taken to include appropriate filters in the air intakes. Again it is considered that filtration to prevent the passage of dust particles larger than 2 microns would suffice. It will be recalled that if longer periods of storage are anticipated, it is common to require air-conditioning and temperatures below $0^{\circ}F$ for photographic materials.

The above-mentioned system of storage applies to photographic papers, films, and plates other than specially coated stock such as that used for medical or industrial X-ray purposes, or emulsions of high sensitivity to gamma and beta radiation such as those used in nuclear research. Materials of this category require additional protection against radiation damage in proportion to their enhanced sensitivity to nuclear radiation. In general these will require additional screening sufficient to attenuate the external radiation dose by a factor of 10-30 times.

The effect of the natural radioactive background may be appreciable in the case of very long term storage of highly sensitive emulsions. This background, which includes cosmic radiation, radiation from surface rocks and from radon in the air, can amount to something like 0.1 roentgen per year, but may vary up to perhaps 10 times this amount where the surrounding rocks are particularly active. An estimate of this background level is made in Reference (1).

While it has been stated that emulsions may be stored underground for periods up to five years, no actual figures are available of the resulting speed changes and fog levels after periods of more than two years. In an emergency however, a supply of film having sensitometric properties slightly inferior to what is normally considered acceptable would be better than no film. It is assumed that stock-piling of black and white photographic film for periods in excess of two years would include a programme for rotation of stocks, periodical testing, and provision of revised exposure and processing tables/data. Some idea of the speed change and total fog to be expected with film stored for up to two years is given in Table 1.

In the event of fall-out settling in areas where underground storage chambers are located, removal of the dust and decontamination of areas around entrances and air intakes should be carried out as soon as conditions at ground level permit. Before any photosensitive material is removed from storage chambers, the region through which the material must be transported should be monitored for activity in order to be certain that it is "safe", bearing in mind the total dose likely to be received during evacuation.

Reference (1) Hazards to Man of Nuclear and Allied Radiations. Cmd. 9780 (H.M.S.O.)

2.5.3. "Ready-use" Storage in Laboratories or Vehicles at Ground Level

Materials stored at ground level should be kept to a minimum if a nuclear burst or the arrival of fall-out is to be anticipated. Photosensitive emulsions kept in windowless brick buildings would receive some shielding from the brick walls, depending on the weight of materials between the source of radiation and the sensitive emulsions. In view of the relative intensities of blast effects and of nuclear radiation it is to be expected that if a building of normal construction is still intact, not more than a negligible amount of promp gamma radiation would reach photographic materials inside, but failure of the windows might permit the subsequent entry of fall-out.

The provision of earth traverses, sometimes favoured as protection against blast and flying debris, will also give an additional appreciable measure of shielding against gamma radiation and neutrons. It will thus be beneficial both against prompt and against delayed radiation. Further details of such traverses are given in Part III, Chapter 3, Section 3.1 of this Manual.

2.5.4. Photographic Chemicals

Chemicals used in photographic processes are not themselves affected by likely doses of nuclear radiation. The greatest danger to chemicals would be through the settling of radioactive fall-out. This could be introduced into the chemicals during manufacture, packing, or in subsequent use in the laboratory where it might enter bottles or containers not properly protected. Such small radioactive particles in chemicals could produce spots on the developed emulsion. These spots would vary in size according to the nature and activity of the fall-out, and large concentrations could reduce the usefulness of a record, as discussed in Section 2.4 above.

TABLE I

Sensitometric Keeping Properties of Photo-sensitive materials

Film Type	Packaging	Time (Months)	-10°F. Speed	Gamma	Fog	Time (Months)	55°F. Speed	Gamma	Fog
Kodak Super XX Aerial Reconnaissance Film	25' x 5¼" in taped cans	orig.	105	.79	.05	12	96	.73	.06
		12	100	.75	.07	12	96	.73	.06
		24	96	.73	.06	24	86	.78	.09
Super XX Sheet Film	8" x 10" in heat sealed foil bags in boxes	orig.	200	.77	.04				
		12	182	.78	.05	12*	177	.78	.06
		24	168	.77	.05	24	156	.78	.06
X-ray Blue Brand	8" x 10" in heat sealed foil bags in boxes	orig.	210	2.80	.06				
		12	190	2.45	.11	12	177	2.70	.13
		24	193	2.60	.19	24	170	2.40	.22
Cine Positive	25 feet x 35 mm in taped cans	orig.	4.9	2.56	.01				
		12	4.9	2.50	.01	12	4.9	2.47	.01
		24	5.2	2.38	.01	24	4.9	2.34	.01
Micro-film Pan	25 feet x 35 mm in taped cans	orig.	3.6	2.48	.02				
		12	3.7	2.92	.02	12	3.7	2.72	.01
		24	3.3	2.59	.02	24	3.5	2.52	.02

*Mottle, at temperatures over 55°F mottle may be expected.

The effect of small concentrations of fall-out of particles less than about 2 microns would be too diffuse to cause fogging in processing unless particles actually settled on the emulsion. Continual motion of film or paper, and the agitation of the solutions would prevent the settling of such particles on the film surface. Particles suspended in a solution would then have little effect, owing to their physical separation from the film surface and their constant motion in solution. A further factor is that a photographic emulsion is less sensitive when wet than when dry.

2.5.5. Decontamination

It will be appreciated that any photographic dark-room or similar installation will require far more stringent decontamination following fall-out than would be the case on purely health physics grounds. This applies particularly in the case of dark-rooms where X-ray, nuclear research or personnel monitoring emulsions are to be processed.

2.6. General Principles for Precautionary Measures

In addition to the routine precautions of a good housekeeping nature discussed in Section 2.5 above, there are numerous ways in which the effect of nuclear radiation may be minimised in the planning of a photographic operation. The first and most obvious means is to minimise the exposure of photographic materials to nuclear radiation. This may involve replanning the operation or experiment so as to ensure that the photographic material is kept as far as possible away from likely or expected sources of nuclear radiation, or that the necessary minimum of radiation shielding is interposed.

The second possibility is to employ the maximum optical exposure. This implies the use of the brightest possible optical image on the slowest possible film for the purpose in hand. Amongst other things this would require using the widest practicable lens aperture, bearing in mind such requirements as depth of focus, lens availability, etc.; it may also be necessary to arrange for enhanced illumination of the object being photographed. This may be done by using a photo-flash under marginal ambient lighting conditions for aerial reconnaissance purposes, or the use of flood or flash lighting in trials.

A third possibility relies on the non-linearity of the exposure curve of most emulsions. In some cases it is possible to arrange that only images above a certain overall minimum appear in the final product. This may lead to some distortion of half-tone values in order to obtain any result at all. It has also been suggested that the use of certain photographic chemicals which act as "anti-fogging" agents may assist in this respect.

It will be appreciated that all the measures discussed in this Chapter amount to making the best of a bad job, in that they use existing materials and techniques with the addition of certain commonsense precautions. The basic requirement remains to obtain the maximum ratio of optical sensitivity to nuclear sensitivity in the photographic process. This is a slightly different problem from that normally facing the manufacturers of such materials. It therefore appears not impracticable that a specific attack on the problem from this point of view would yield significant results.

D1/57
February, 1960.

Part VIII
Chapter 3
Preliminary

Chapter 3. Effects of Nuclear Weapons on Explosives

3.1 Introduction.

3.1.1 Types of explosives

3.1.2 Initiating explosives

3.1.3 High explosives

3.1.4 Propellants

3.2 Blast Effects

3.3 Thermal Effects

3.3.1 Introduction

3.3.2 Summary of paper by Cook

3.3.3 Summary of paper by McGuire and Law

3.3.4 Results from Operation Buffalo

3.4 Nuclear Radiation Effects

3.4.1 Absorption of nuclear radiation by explosives

3.4.2 Effect of irradiation on explosives

3.4.3 Energy deposition in typical explosives

3.4.4 General conclusions

H.74155D

3.1 Introduction

3.1.1 Types of Explosives

Explosives may be classed into three main groups, namely:- initiating explosives, high explosives, and propellants. Initiating explosives are very sensitive and are readily detonated by small amounts of thermal, mechanical or electrical energy. As their name implies their chief use is to initiate detonation in the main explosive charge. Initiating explosives are too sensitive to mechanical shock and friction to be employed in more than minimum quantities and their explosive power is relatively low.

High explosives are filled into warheads, bombs, shell, etc. and are also used uncased for demolition purposes. They are much less sensitive than initiating explosives. The type of high explosive is carefully chosen to give the most efficient performance in the particular role required.

Propellants are not detonated but are burnt very rapidly under pressure so as to produce gases at high temperature which propel the shell or warhead along the desired trajectory.

3.1.2 Initiating Explosives

The more common initiating explosives are salts of heavy metals, for example, lead azide, lead styphnate, lead dinitroresorcinate (LDNR), and mercury fulminate, and are frequently mixed with other substances to obtain specific effects. Detonators for use in the initiation of explosive systems may have one or more initiating compositions pressed as increments, depending upon the particular use envisaged; their initiating power may be increased by filling the lower portion with tetryl. Initiating substances are also employed in "caps" for igniferous trains in propellant systems. For instance, in a gun cartridge, a cap is used to ignite the gunpowder in a primer which in turn ignites the main propellant charge. Mercury fulminate, which has relatively poor thermal stability, has been replaced by lead azide for use in detonators; and in cap compositions is being replaced by LDNR.

3.1.3 High Explosives

The most common high explosive substances used in the British Service are tetryl (trinitrophenyl-methyl-nitramine) slso known as CE, TNT (trinitrotoluene), RDX (cyclo-trimethylene-trinitramine), PETN (pentaerithritol-tetranitrate), and ammonium nitrate. Tetryl is mainly used as an intermediary between the initiator and the main explosive charge. Apart from TNT, which is frequently employed alone, the other materials are normally used in mixtures of which the following are the most common:-

Composition (Major Ingredients)	Designation
RDX/TNT	60/40 mixture known in U.S.A. as "Composition B"
RDX/TNT/Al with wax	Torpex
Ammonium Nitrate/TNT	Amatol
Ammonium Nitrate/TNT/Al	Minol
RDX/Wax	-
RDX/Wax/Al	-
TNT/Al	Tritonal
PETN/TNT	Pentolite
RDX/Oil or RDX/Grease	Plastic Explosive

The wax is added to high explosives to reduce sensitivity. Both TNT and the wax used in H.E. fillings melt at comparatively low temperatures, enabling the explosive to be cast from steam-heated vessels. This feature, while facilitating filling by casting, may lead to exudation through screw-threads if stores are heated to temperatures above 70°C. Aluminium is added to enhance blast and incendiary effects; explosives containing aluminium evolve gas on storage as a result of interaction between the aluminium and residual moisture and arrangements have to be made for the periodic venting of large thin walled stores, such as Naval mines and depth charges, to prevent distortion by internal pressure.

3.1.4 Propellants

Propellants may be broadly classified on the basis of their physical form into solid, plastic and liquid.

The traditional solid propellants, as used in guns, and in many rocket and G.W. applications, are usually based on nitrocellulose and nitro-glycerine. In this form they are termed "double base". Without the addition of nitroglycerine they are termed "single base". In addition the important class of "flashless" propellants for guns have a third major ingredient: picrite (nitroguanidine). Stabilisers must always be included to prevent a dangerous accumulation of the decomposition products of nitric esters. Other substances may be added in small proportions to achieve special properties, for example, inorganic salts to control burning rates or to reduce flash.

In recent years other types of solid propellant have been developed, principally for large rocket motors. In some of these, polymers other than nitrocellulose have been employed and large proportions of inorganic salts have been included as the main oxidant. Such propellants are sometimes referred to as "composite" propellants. Plastic propellants are a special form of composite propellant in which a large proportion of inorganic oxidant, for example, ammonium picrate and ammonium perchlorate, is suspended in an inert "binder" to give a putty-like material for direct filling into rocket motors.

Liquid propellants are usually single component, designated mono propellants, (for example iso-propyl nitrate) or have two components, for example, hydrogen peroxide/petrol, liquid oxygen/alcohol, nitric acid/aniline. In the case of two component propellants the components are stored separately until the moment of mixing in the rocket chamber and the explosive hazards in storage are thus reduced.

3.2 Blast Effects

The main effects of blast from nuclear weapons on explosives may be considered to be due to the direct effects of the blast wave itself, particularly the over-pressure, to the effects arising from displacement by the associated drag forces and to the effects of secondary missiles.

Before discussing these in some detail, it is perhaps advisable to state that in most applications of military interest explosives are not used bare, but are contained in a metallic or similar casing. There are some exceptions to this, notably the bare slabs of plastic explosive used for demolition purposes.

During research and development, explosive constituents are tested for their resistance to shock, etc. When an explosive is part of a store it has to withstand certain rough usage trials to ensure that it is not initiated, or rendered unsafe for normal use. Some of the more usual tests are discussed briefly below, mainly in order to indicate the magnitude of the blast or overpressure required to initiate the explosive.

For instance, during research into new initiating explosives, the suitability of a proposed composition is tested by its behaviour in the ball and disc impact test and in a friction test. In general it can be said that these tests are more severe than would be the case in practice, even when the store is subjected to the blast from a nuclear explosion. When it is used in a detonator which is fitted into a fuze or similar component, the initiating explosive is further tested for resistance to rough usage by dropping it 30 feet in a 65 lb. block on to a steel anvil.

The sensitiveness or susceptibility of high explosives to initiation by shock is tested during their development in two main ways, (1) by detonating a control sample of explosive at various distances from the sample under test (called the gap test), (2) by firing small steel pellets or fragments into the test sample at various velocities. In the former test the gap (which may be either air or a metal) between the samples is varied, in order to determine the distance at which 50% detonation of the sample is obtained. It has been found that the shock wave peak pressure required for detonation is of the order of some thousands of p.s.i. In the latter test the object is to determine the velocity at which 50% of ignitions of the sample is obtained. This test has shown that high velocity fragments (some thousands of f/s) are necessary.

The results of these tests have been roughly confirmed by trials in which stocks of ammunition have been exposed to the effects of blast and fragments from the detonation of large amounts of high explosives. These have indicated that there is little chance of initiating the explosive by fragments unless they are travelling at high velocities (thousands of f/s) and that blast overpressures have to be high to affect either boxed or unboxed ammunition. Following these trials it has been laid down for stocks of ammunition that the safe storage distance is $2W^{\frac{1}{3}}$ feet (where W is weight of H.E. in stack in lb.). This distance corresponds roughly to an overpressure of 500 p.s.i.

The initiation of propellants to ignition by shock or fragments also requires very high overpressures or very high fragment velocities. Both explosives and propellants can be initiated or ignited by being nipped between two surfaces. The basic principles involved in the ignition process of propellants may bear some similarity to that involved in the initiation of H.E., in that the latter can sometimes occur by a process of burning to detonation. There is also the possibility that the propellant charge

in a rocket or cartridge is damaged sufficiently by an impact to cause malfunction when used later, but in practice the external metal components would also be damaged, so that the ammunition would be discarded.

Before the blast wave reaches any particular target, that target has already been irradiated by the thermal and initial nuclear radiation. The effects of this irradiation are discussed in subsequent sections. In this section it is only necessary to surmise whether such irradiated material, which has not already been initiated, will be more liable to initiate by the subsequent shock from blast wave. No laboratory trials to test the overall effect have been carried out, but many explosives have been exposed to the effects of nuclear explosions (see references 1 and 2 at the end of this section).

The results of these trials have confirmed, with one possible exception, that peak blast overpressures of 100 p.s.i, and less do not directly cause the initiation of the main explosive components of ammunition. The exception consists of bare detonators which were initiated, but it is probable that many of these were set off by thermal radiation. Additionally, some slabs of plastic explosives have been exposed bare, and although most have been broken up and dispersed by the blast, there has been no evidence suggesting that the slabs have been initiated at peak blast overpressures below 40 p.s.i.

It can be concluded, therefore, that explosives and explosive stores will not be initiated by the blast effects, except at such small distances that the other components of the ammunition are themselves very seriously damaged.

From the results of Operations Totem and Buffalo it is apparent that ammunition exposed on the ground to a nuclear explosion is liable to be displaced considerably at distances where the peak blast overpressures are of the order of 15 to 20 p.s.i. With the possible exception, as before, of bare detonators, there have been no indications that the explosive components have been initiated by shocks sustained in this displacement, except by mechanical damage to the initiating mechanism.

As might be anticipated the effects from missiles have also been found to be insufficient to initiate the explosive components of ammunition, except through the normal explosive train (e.g., at least one percussion cap was initiated by a blow from a flying object).

References

1. AWRE Report T84/54. The Effects of an Atomic Explosion upon Ammunition. (Confidential).

2. AWRE Report (to be published). Operation Buffalo. Explosives Group Final Report, Part 7.

Other references on this subject will be found in the Bibliography, Part IX, Chapter 6.

3.3 Thermal Effects

3.3.1 Introduction

The effect of thermal radiation on explosives has been studied theoretically by McGuire and Law (1) and by Cook (2). Using different techniques and approximations both papers predict the temperature rise within an explosive that is shielded from the radiation by a thin slab of metal. Ignoring the effects of nuclear radiation from an atomic explosion, critical conditions are established under which the explosive will remain undamaged. These papers are summarised and compared below.

Experimental study is so far restricted to the tests conducted during Operation Buffalo (3). Little comparison with theory is possible owing to lack of data on the explosives used, and to the small radii of the shell.

3.3.2 Summary of paper by Cook (Reference 2)

Cook considered a pulse of high intensity thermal radiation incident on a target consisting of a steel plate covering a mass of high explosive. The radiation is partly absorbed at the steel surface and heat is conducted through the steel and into the explosive. It is assumed that the latter liberates heat according to the classical Arrhenius formula.

A radiation pulse of the form:-

$$\Phi(t) = Ct \exp(-\alpha t), \qquad (1)$$

was chosen, where C and α are constants. This function is the simplest analytical form exhibiting the correct qualitative features, though it ignores the radiation of extremely high intensity delivered from the weapon during the first few milliseconds. However, it is known that the thermal radiation delivered during this period is only about one or two per cent of the total. It was also assumed in this paper that loss of heat from the steel surface by convection or back radiation could be ignored.

Under these conditions the heat conduction equations were integrated on a digital computer to find the time to ignition, t_e, of the explosive, after the onset of the pulse. This time depends on the following parameters:

Heat of reaction	$= Q$ cals gm.$^{-1}$
Reaction rate	$= Z \exp(-E/RT)$ sec^{-1}
Thermal conductivities of steel and explosive	$= k_1, k_2$ cal cm^{-1} sec^{-1}($^{\circ}$C)$^{-1}$
Specific heats of steel and explosive	$= C_1, C_2$ cal.gm^{-1}($^{\circ}$C)$^{-1}$
Thermal diffusivities of steel and explosive	$= \kappa_1, \kappa_2$ cm.^{2} sec^{-1}

together with the constants C and α of equation (1), the steel thickness, d cms., and the initial temperature of the system, T_o $^{\circ}$C.

For a better understanding of the effect of these parameters on the ignition time, dimensionless variables were used, these being defined by the relations

$$
\begin{aligned}
\xi &= 10^{-7}\,(\rho_2 RQZ/k_2/)^{\frac{1}{2}} x = ax \\
\tau &= 10^{-14}(RQZ/C_2E)\ t = bt, \qquad (2) \\
\theta &= (R/E)\ T = cT,
\end{aligned}
$$

where x, t, and T are distance from the steel surface, time, and temperature, respectively. The coefficients a, b, and c are shown for three explosives in the following table

Table 1

Explosive	RDX	Tetryl	NENO
a	1700	29.34	21.5
b	2770	0.83	0.21
10^4c	0.418	0.517	0.56

Further, the following quantities were defined,

$$\Gamma = Bc/a\ b\ k_1 \qquad (3)$$

$$\mu = \alpha/b \qquad (4)$$

$$\zeta_o = \left(K_2/K_1\right)^{\frac{1}{2}} a\ d \qquad (5)$$

where B is the product of the absorptivity coefficient of the steel surface with C.

The dimensionless ignition time, τ_c, then depends on the four parameters θ_o, Γ, μ, and ζ_o, which correspond physically to the initial temperature of the system, the constants C and α of equation (1), and the steel thickness d.

Two series of computations are reported in (2). In the first of these the general features of the behaviour of τ_c with respect to these parameters is examined and, in the second series, the case for which the explosive is RDX is examined in detail.

The results for the first series are shown graphically in Fig.1 where τ_c is plotted as a function of ζ_o, defined by equation (4), for various values of θ_o, Γ, and μ. The values of θ_o, Γ, and μ to which the curves labelled I - VII correspond are given in Table II.

Table II

Curve	θ_o	Γ	μ
I	0.0171	0.4964	14.0
II	0.0171	0.5433	14.0
III	0.0171	0.6641	14.0
IV	0.0171	0.0542	4.0
V	0.0151	0.0875	4.0
VI	0.0161	0.0875	4.0
VII	0.0171	0.0875	4.0

In this series, it was assumed that

$$\kappa_1 = 0.12 \text{ cm}^2 \text{ sec}^{-1} \qquad \kappa_2 = 0.006 \text{ cm}^2 \text{ sec}^{-1}$$
$$k_1 = 0.11 \text{ cal.sec}^{-1} \text{ cm}^{-1} (^\circ C)^{-1} \qquad k_2 = 0.0005 \text{ cal.sec}^{-1} \text{cm}^{-1} (^\circ C)^{-1}$$

The results obtained in the second series, in which the explosive is RDX, are shown in Fig.2, where the explosion ignition time is plotted against the steel thickness for values of the parameter B, listed in Table III. In all these results

$$\alpha = 2.078 \text{ sec.}^{-1}$$
$$T_o = 28.4\ ^\circ C.$$

Table III

Curve	B
I	565.4
II	621.3
III	737.7
IV	828.3
V	957.8
VI	1113.0

From the results of the first series of computations, shown in Fig.1, the following physical conclusions are drawn.

(i) For a given radiation pulse (C and α fixed), and for a given initial temperature, there exists a critical value of d, equal to d^*, say, such that, if the steel thickness exceeds d^*, there will be no explosion.

(ii) As far as the critical thickness is concerned, the shape of the radiation pulse is unimportant, the important quantity being the total radiation absorbed. This result also implies a critical minimum value of the total radiation for ignition to occur. Curves III and IV were plotted with the same value of Γ/μ^2, which is proportional to the total absorbed radiation, B/α^2. These curves have a common critical value of ζ_o, and hence of d.

In the case of tetryl, for which the coefficients a, b, and c are given in Table I, these value of θ_o correspond to 19°C, 38°C and 58°C. Thus for a 40° rise in the initial temperature the critical thickness is increased by about 20 or 25 percent. The two extremes of T_o, 19°C and 58°C, correspond roughly to room temperature and tropical storage temperature.

Returning to the specific example of RDX, the critical thickness of steel, d^*, may be obtained as a function of S as follows.

Table IV

B/α^2 (cal cm^{-2}	d^* (cm.)
258	1.07
222	0.925
192	0.80
171	0.71
144	0.595
131	0.545

These results are approximately linear but any extrapolation should be treated with caution. It is thus possible to determine the thickness of steel casing necessary to protect the explosive in a shell standing at a specified distance from the centre of the burst. As an example, suppose the radiation derives from a nominal 20 kiloton atomic weapon. Then the target for which d = 0.55cm., and the absorption coefficient is 0.6, is vulnerable to thermal radiation at a distance of 0.5 km., since the total incident thermal radiation on a clear day here is of the order of 203 cal cm^{-2}. The general conclusion which may be drawn from these results is that, if the target is sufficiently close to the burst to be vulnerable to thermal radiation, it would, in any case, suffer severe damage from the blast wave.

It is pointed out that, though the dimensionless solutions are accurate to within two percent, the parameters that are involved in the physical solutions are only approximate. For instance, to determine a value of d^* corresponding to a given critical dimensionless thickness, equations (2) and (5) are used to find the relation.

$$d^* = 10^7 \left(\frac{E\, C_2\, \kappa_1}{RQZ}\right)^{\frac{1}{2}} \zeta^*$$

Apart from the density, conductivity and specific heat of the explosive, the parameters are rather uncertain.

3.3.3 Summary of paper by McGuire and Law (Reference 1)

In the investigation conducted by McGuire and Law, a similar model was used to that described above. Additionally, heat loss by convection from the outer surface was incorporated, though heat arising from the chemical reaction of the explosive was neglected.

Four cases were considered: two with a steel container and two with brass. The total heat, S, delivered by the pulse, necessary to raise the metal/explosive interface 130°C and 70°C was determined for each container. The ambient temperature was assumed to be 30°C, and in each case the metal thickness was 0.318 cm. In particular the results in Table V apply to a propellant with thermal conductivity 5.5×10^{-4} cal.cm^{-1} sec^{-1} $(^\circ C)^{-1}$, density 1.5 gm cm^{-3}, and specific heat 0.35 cal. $gm^{-1} (^\circ C)^{-1}$.

Table V

Container	Quantity of heat (cal.cm.$^{-2}$)	
	Temperature = 160°C	Temperature = 100°C
Steel	39.4	21.2
Brass	35.4	19.2

The temperatures in Table V were chosen because a propellant ignites at 160°C or is rendered useless at 100°C. An example of a temperature-time curve is shown in Figure 3.

The accuracy of this method is quoted as two per cent provided the minimum radius of curvature of the container is 2 in. The computations were repeated while neglecting the heat loss from the outer surface and it was found that the temperature-time curves were left substantially the same. This justifies Cook's assumption mentioned in the first paragraph of 3.3.2 above.

Because chemical reaction is neglected within the explosive, the temperatures in Table V and figure 3 are proportional to the intensity of the pulse. The results also apply to any material with the same physical properties as the propellant considered.

The explosive RDX, considered in detail in Cook's report, has roughly the required properties and initial temperature, so that the two methods may be compared.

From figure 2 it appears that a pulse of 130.94 cal.cm^{-2} incident on steel of thickness 0.315 cm causes ignition of RDX after 1.6 sec. Scaling the results of figure 3 to apply to a similar pulse it is found that the interface has the ignition temperature of RDX after approximately 0.8 sec. Thus the first method gives an ignition time of about twice the value of that given by the second method.

It is not thought that such an error could be explained by the small differences of the thermal properties used in each method, especially since the assumptions (e.g. the neglect of a chemical reaction and of heat loss from the surface) tend to keep the results in closer agreement.

3.3.4 Results from Operation Buffalo (Reference 3)

Little comparison is possible between the experiments conducted in Operation Buffalo and the above theories. This is partly due to the lack of reliable data on the explosives used, but also because the inner radius of the cases was only 2.86 cm., which is outside the limit for reasonable accuracy set by the theories. It is to be expected, then, that the ignition times predicted by theory will be considerably smaller than realised in the experiments.

In one instance, (Case No.77 reference (3)), a shell containing an RDX beeswax mixture was exposed to a total incident radiation of 425 cal cm^{-2}. The container was made of steel of thickness 0.635 cm., and this protected the explosive from all damage. Assuming an absorption coefficient of 0.6, the total absorbed radiation would be 255 $cal.cm^{-2}$. From Cook's results it may be estimated that this radiation would cause ignition of RDX, after approximately 2.5 sec. and that for no damage to occur the steel would have to be 0.9 cm thick.

Other experiments in Operation Buffalo show no damage to the explosive even if the steel thickness is as low as 0.159 cm. but comparison is not possible since these results are outside the scope of Cook's computations.

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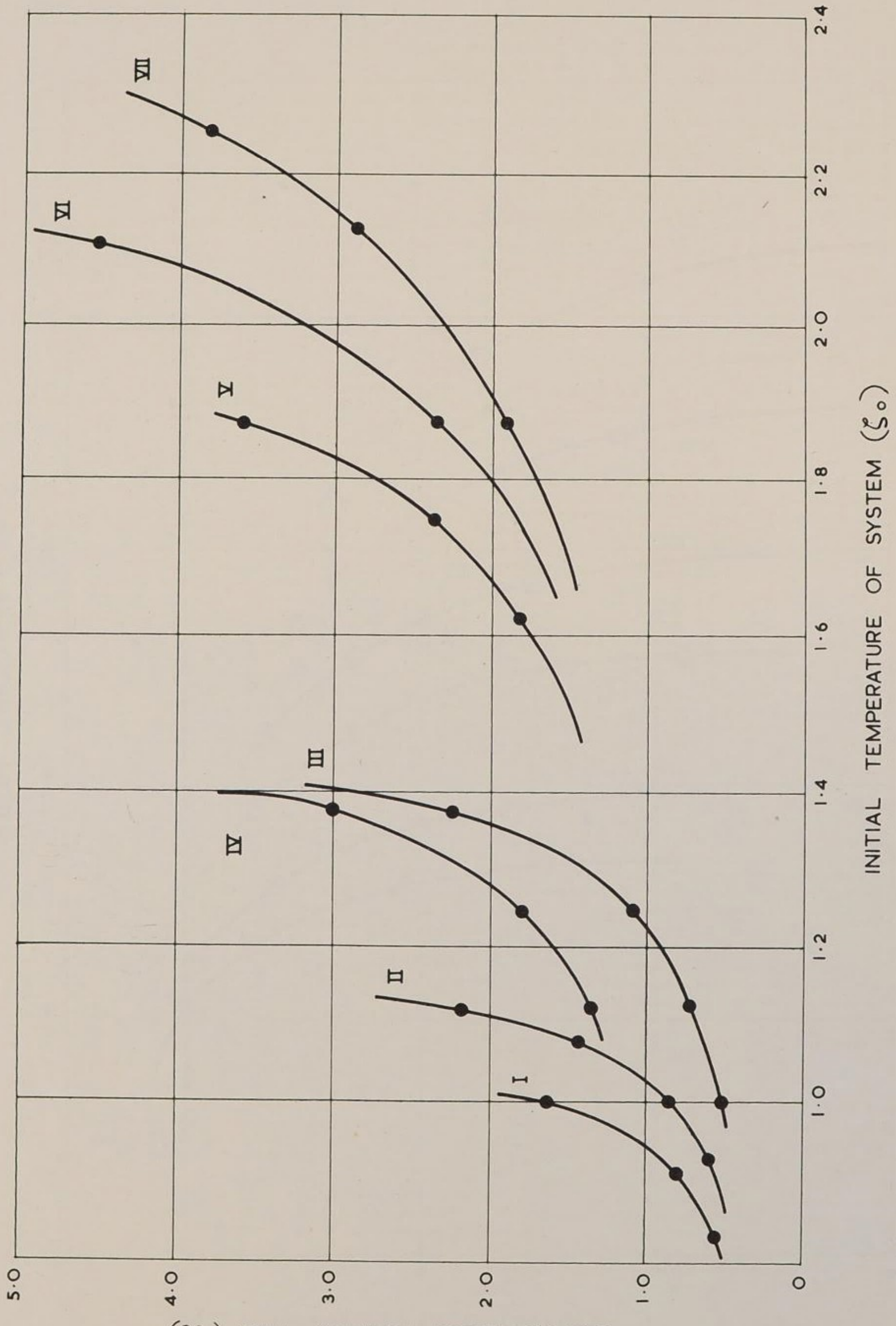
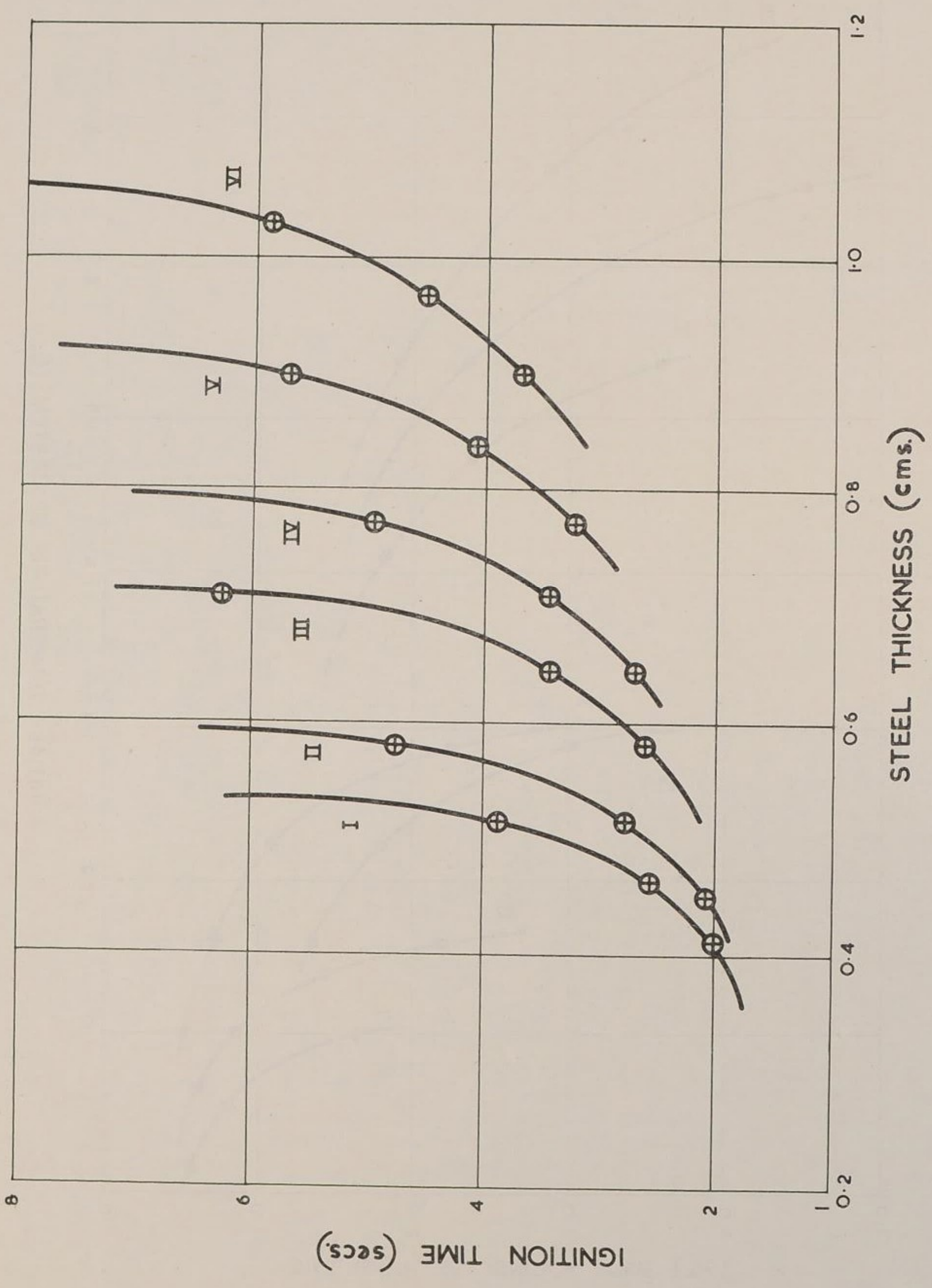


DEPENDENCE OF IGNITION TIME ON INITIAL SYSTEM TEMPERATURE

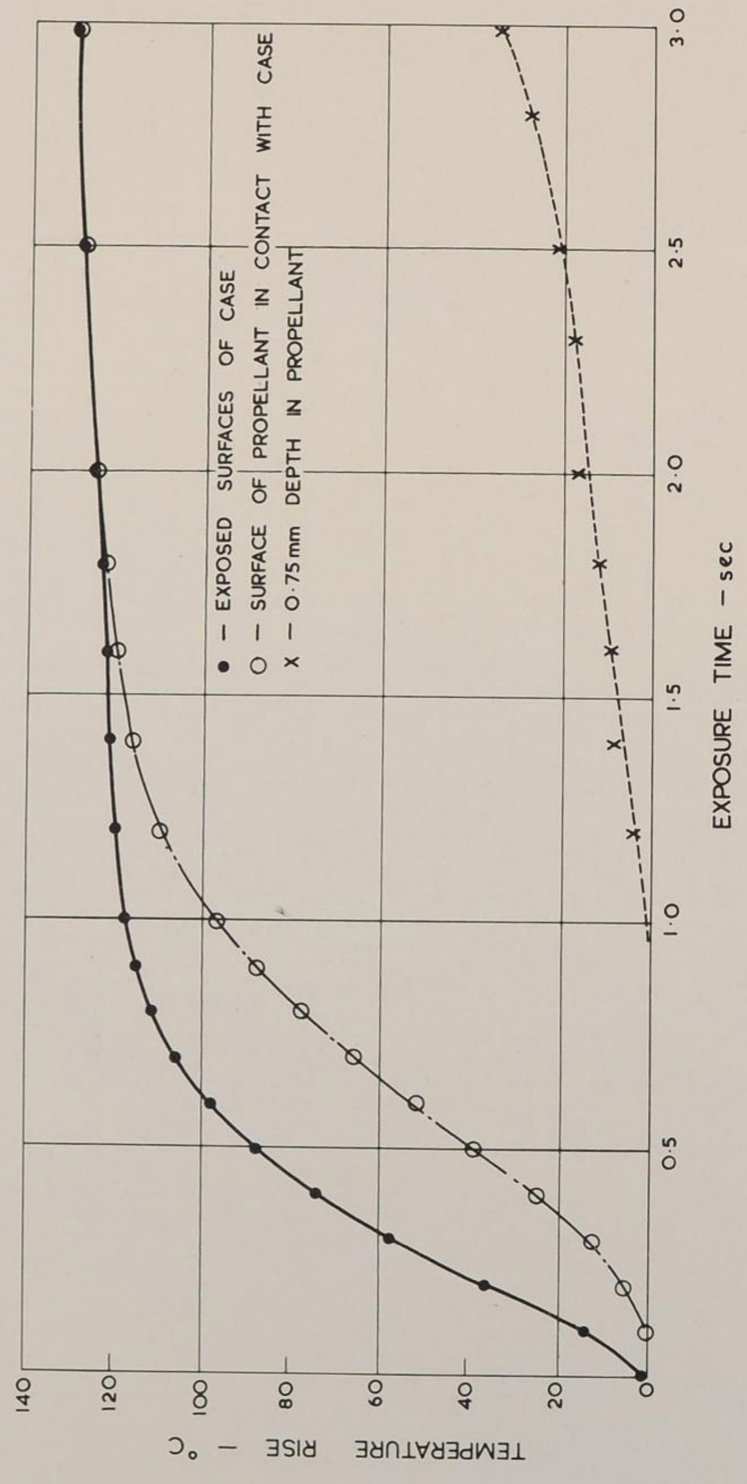
CONFIDENTIAL



IGNITION TIME VS. STEEL THICKNESS FOR SEVERAL RADIATION PULSES (RDX.)

CONFIDENTIAL

CONFIDENTIAL



TEMPERATURE RISE OF PROPELLANT AND STEEL CASE
(39·4 cal/cm² incident)

CONFIDENTIAL

3.4 Nuclear Radiation Effects

3.4.1 Absorption of nuclear radiation by explosives

(a) Absorption of gamma rays

An atomic explosion produces several different types of nuclear radiation. These are fission fragments, alpha particles, beta particles, neutrons and gamma rays. Only neutrons and gamma rays have a long range and are likely to be present in significant concentrations at even short distances from the centre of the explosion. Therefore only gamma rays and neutrons will be considered. The primary effect of gamma rays on explosives will be the same as their effect on other substances. A gamma ray photon loses its energy over a long path by interaction with the electrons of the atoms forming the explosive and these electrons will be left in specially energetic states. Some of these primary electrons may be given sufficient energy to react with other electrons. Some of the photon energy will be given up as heat, and this will be dissipated through the solid with great rapidity. In explosives, as a result of these effects decomposition will be produced along the path of each photon.

(b) Absorption of neutrons

Fast neutrons will lose their kinetic energy by collision with the nuclei of the atoms forming the explosive. A neutron may penetrate a considerable distance before suffering an interaction but at each interaction it will lose a large fraction of its energy, up to a maximum of a half for an interaction with a hydrogen atom. The atomic nucleus will receive this kinetic energy and will fly out of its normal position in the explosive. It will then lose this energy rapidly in a very short path by exciting electrons of other atoms, and as heat. Again, in explosives the passage of a fast neutron will cause decomposition to occur along its path. The decomposition, however, instead of being spread fairly evenly along the path, as in the case of gamma rays, will be concentrated in particular regions.

Thermal neutrons are moving so slowly that they have no kinetic energy to give up and they only produce an effect in an explosive if they are capable of undergoing a nuclear reaction with the atomic nuclei of the explosive. One such reaction, of particular interest in explosive science is the (n, p) reaction with nitrogen, i.e. $n + {}^{14}N \rightarrow {}^{14}C + p$. Here a proton of high energy (0.61 MeV) is produced. This will lose its energy very rapidly giving a concentrated region of decomposition. Another thermal neutron nuclear reaction is with the hydrogen nucleus when a high energy gamma ray photon (2.2 MeV) is produced.

(c) Energy deposition

In general only a fraction of the total radiation incident on an explosive charge is absorbed by the charge. The rest is carried by the fraction of the incident radiation that goes straight through the charge. The energy of the absorbed radiation is transferred to the explosive, and in the case of thermal neutrons the energy produced by nuclear reactions, e.g. the (n, p) nitrogen reaction, can be considered as additional energy transferred to the explosive. The "energy deposition" produced in a particular explosive by irradiation with a particular radiation can be calculated and this is found to be the best general factor to use in a quantitative assessment of the effects of nuclear irradiation on explosives. This does not mean that for the same energy deposition gamma ray irradiation and neutron irradiation will always give quantitatively equivalent effects;

for a given energy deposition, bomb neutrons are thought to be 1.7 times as effective as gamma radiation in producing physiological effects in animals (1), and similar differences are sometimes found with explosives.

3.4.2 Effect of irradiation on explosives

(a) Possibility of immediate explosion

The absorption of a nuclear particle by an explosive as noted above, gives a region in which a transient high temperature is produced and decomposition takes place. This decomposition liberates chemical energy which tends to maintain the high temperature and this will in itself encourage further decomposition. If more energy is produced in this region than can be dissipated, e.g. by thermal conduction, decomposition will continue in the "hot spot" at an accelerating rate and the "hot spot" will grow rapidly leading to an explosion. It is conceivable therefore that absorption of a single nuclear particle by an explosive charge could lead to an explosion. However, it has been shown experimentally (2) that spherical "hot spots" of size less than 10^{-3} to 10^{-5} cms. (these were produced by means other than nuclear irradiation), are quenched by heat losses and do not grow to give explosion. The "hot spots" produced by nuclear irradiation are at least an order smaller in size than this, and other experiments (3) have shown directly that the region of decomposition produced by a single nuclear particle is too small and the high temperature is maintained for too short a time for growth to explosion to occur in any useful explosive. Even fission of a uranium atom embedded in an explosive, will not of itself give detonation (11). An immediate explosion can, therefore, only be produced by the aggregate effect of the absorption of a large number of particles, giving sufficient energy liberation in a particular region to constitute an effective hot spot.

Work on the initiation of silver azide by visible and ultra-violet light irradiation and by electron bombardment (4) has shown that explosions occur only when the absorption of radiant energy is so great that a marked rise in the temperature of the explosive is produced. A similar effect is to be expected with nuclear irradiation, and energy depositions of the order of 10^8 ergs. per gram, delivered in so short a time that heat dissipation processes are unimportant, are probably necessary to produce immediate explosion in initiators. For high explosives and propellants it is probable that an energy deposition an order greater would be required. No direct measurements have been reported and the estimated values given here may be an order wrong either way.

(b) Effect of irradiation on the power of explosives

The next four sub-sections (b), (c), (d), (e), will consider permanent changes produced in explosives, which may affect their performance some long time after the irradiation has ceased. For all these permanent effects the evidence indicates that it is the total energy deposition which is important; whether it is absorbed rapidly or slowly, continuously or intermittently does not matter. The power of an explosive will be reduced proportionally to the fraction of the explosive decomposed by the irradiation. It is known that ionisation of air by nuclear irradiation requires an average energy of about 30 ev and other similar processes in solids take from 10 to 30 ev (5). A moderate reduction in the power of lead azide, say five per cent, should therefore be produced by an energy deposition of about 10^{10} ergs per gram. An American report (6) describes the irradiation of several explosives with the 0.41 Mev gamma irradiation from a gold source. 52 days irradiation of lead azide, corresponding to an

energy deposition of 10^{10} ergs per gram gave 4% decomposition, confirming the above estimate. For the same energy deposition the decomposition of R.D.X. and T.N.T. were respectively about 20% and 1% of the lead azide value. Lead styphnate had a very low decomposition rate (approximately that of T.N.T.) but nitroglycerine was rather higher even than lead azide. Mercury fulminate had a 30% decomposition after only half the standard dosage and lost most of its power. The latter is therefore particularly sensitive to irradiation, which is not unexpected in view of its known instability. It may be noted that except for mercury fulminate, the liberation of chemical energy from the small amount of decomposition is less than $1/_{10}$th of that absorbed from the nuclear radiation. In these decompositions the activation energy is supplied directly by the radiation and the temperature coefficient is therefore small e.g. the decomposition of lead azide was increased about five times only by raising the temperature from -40 to + 71°C.

(c) Effect of irradiation on the sensitivity of explosives

Permanent changes in the sensitivity of explosives are important because an increase in sensitivity may make them unsafe for handling and a decrease in sensitivity may adversely affect their functioning. The sensitivity of an explosive should be increased by nuclear irradiation, because of the resulting decomposition and the autocatalytic effect. At very high dosages the sensitivity may fall again and in any case the loss of power resulting from the decomposition will become the dominant effect. The effect of nuclear radiation on the sensitivity of initiators is discussed in detail in a report (7) describing the effect of irradiation with high energy x-rays on the thermal explosion of Service lead azide. Later work (8) shows that slight changes are produced in the decomposition characteristics of lead azide by irradiation at an energy deposition as low as 10^6 ergs./g. An impact test however showed sensitization only at doses of about 10^9 ergs./g. and even at this level a friction test, capable of clearly differentiating Service lead azide and pure lead azide, showed no sensitization. Pile radiation, for which the energy deposition comes in roughly equal parts from gamma radiation and thermal neutrons, gave exactly similar effects for the same energy deposition. Quantitatively similar results for gamma and pile irradiation and impact and stab sensitivity tests are described in American reports (6,9). It has already been noted that lead styphnate is resistant to gamma radiation and no change in impact sensitiveness was produced by doses up to 10^9 ergs./g., nor was the character of subsequent thermal decompositions changed. Pile irradiation (10) at doses of this order again gave negligible decomposition, but subsequent thermal decomposition characteristics were markedly changed. This is probably the most striking example to date of different effects being produced by gamma and neutron irradiation. For high explosives and propellants similar results are obtained (6), the more sensitive materials (e.g. nitroglycerine, R.D.X.) showing effects at energy depositions of 10^9 ergs./g. and above. In general, changes in sensitivity are found in some explosives at energy depositions of about 10^9 ergs./g. and no significant effect would be expected at energy depositions less than 10^8 ergs./g.

(d) Effect of irradiation on the stability of explosives

It has been noted that the partial decomposition of an explosive produced by nuclear irradiation, because of the autocatalytic effect, could in theory give a reduction in the stability of the explosive. The process may be similar to the increase of sensitivity discussed under (c) above. It is to be expected that an appreciable decrease in stability would be produced by an energy deposition of the same order as that which gave an appreciable increase in its sensitivity, i.e. greater than 10^8 ergs per

gram. It should be noted that this effect will be most important for explosives that inherently do not have good stability. If a particular explosive's stability is such that it has a useful life of one year, absorption of sufficient nuclear radiation to reduce the useful life to one tenth may be significant. For another more stable explosive, say with a useful life of a hundred years, reduction of its useful life to one tenth would probably not matter. The best estimate that can be given is that an energy deposition of greater than 10^8 ergs. per gram may cause a substantial fractional change in the stability. Whether or not this would have any practical effect for any particular explosive is doubtful.

(c) Effect of irradiation on the physical properties of explosives

In general a small change in the physical properties of an explosive will not seriously affect its functioning. However, in special cases e.g. with propellants, changes in hardness etc. may be important. There has been considerable work on inert plastics and it is known that the effect of irradiation is to split chemical bonds and produce cross-linkages with a consequent increase in the average molecular weight of the material. This increases viscosity, hardness etc. A. Charlesby reports (8) that an energy deposition of 7.4×10^9 ergs./gram gives 1 per cent linking of carbon atoms in perspex. An energy deposition of about 10^{10} ergs./gram is probably required to produce a significant change in the physical properties of explosives.

3.4.3 Energy deposition in typical explosives

It has been stated above that energy deposition is the best factor to use in a quantitative assessment of the effects of nuclear irradiation on explosives. The energy depositions in lead azide and T.N.T. for various types of irradiation have been calculated and are summarised in Tables I and II. The values given are only approximate and no corrections have been made for "bad geometry." The energy depositions in other high explosives and propellants containing carbon, hydrogen, nitrogen and oxygen only, will probably be insignificantly different from the T.N.T. values and the lead azide values will probably be approximately correct for other initiators which are salts of heavy metals.

Table I

Energy deposition in lead azide and T.N.T. Due to gamma irradiation

gamma energy	Energy deposition in ergs per gram per roentgen	
(Mev)	lead azide	T.N.T.
0.5	75	123
2.0	74	124
5.0	103	125
10.0	151	124

Table II

Energy deposition in lead azide and T.N.T. due to thermal neutrons

Invident neutron flux	Energy deposition in ergs per gram	
per cm^2	lead azide	T.N.T.
10^9	21	14
10^{12}	2.1×10^4	1.4×10^4
10^{16}	2.1×10^8	1.4×10^8

The energy deposition from thermal neutrons is almost entirely due to the nitrogen content of the materials by the (n, p) reaction mentioned above. The energy deposition per gram of nitrogen by this reaction is 7.4×10^{-8} ergs. for unit incident neutron flux per cm^2.

Table III

Energy deposition in lead azide and T.N.T. due to fast neutrons

For these calculations it has been assumed that each neutron suffering an interaction with a target nucleus gives up all its energy to the target.

Incident neutron energy	Energy deposition in ergs per gram per neutron	
	lead azide	T.N.T.
100,000 ev.	1×10^{-8}	6×10^{-8}
1 Mev	6×10^{-8}	4×10^{-7}
10 Mev	5×10^{-7}	1×10^{-6}

Table IV

Estimated energy depositions to produce particular effects in lead azide and T.N.T.

Effect	Energy deposition in ergs/gram	
	lead azide	T.N.T.
Immediate explosion	10^8	10^8
Decrease in power	10^{10}	10^{10}
Increase in sensitivity	10^8	10^9
Decrease in stability	10^9	10^9

Table V

Neutron and gamma doses to give energy deposition of 10^8 ergs per gram in lead azide and 10^9 ergs per gram in T.N.T.

Type of radiation	Dose	
	lead azide	T.N.T.
gamma rays	10^6 roentgens	10^7 roentgens
Thermal neutrons	5×10^{17} per sq.cm.	5×10^{18} per sq.cm.
1 Mev neutrons	2×10^{15} " " "	2×10^{15} " " "
10 Mev neutrons	2×10^{14} " " "	10^{15} " " "

For mixed irradiation the effects are additive.

3.4.4 General conclusions

On theoretical grounds it is to be expected that nuclear irradiation will change the properties of initiators, high explosives and propellants. The experimental evidence supports this view, and necessarily crude estimates indicate that at energy depositions greater than 10^8 ergs per

gram for initiators, and 10^9 ergs per gram for high explosives and propellants, there is a possibility of (a) immediate explosion and (b) if (a) does not occur, increased sensitivity and decreased stability. The dosages of gamma radiation, thermal neutrons and fast neutrons needed to give this energy deposition are summarised in Table V.

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PART IX - BIBLIOGRAPHY

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Note - In each sub-section reports are listed by country of origin, and the pages are therefore numbered A.1 ... for American reports, B.1 ... for British reports, and C.1 ... for reports of miscellaneous origins.

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1.3. Thermal Radiation from Nuclear Weapons. Propagation.
1.4. Nuclear Radiation and Fallout from Nuclear Weapons, Shielding.

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2	U.S. Government Printing Office	Unclassified	The Effects of Nuclear Weapons, 1957.
3	U.S. Government Printing Office	Unclassified	The Effects of Atomic Weapons, 1950.
4	U.S. AFSWP-602 (DRB 55/12847) (MOD. Ref. No.115)	Confidential	A Study of the Influences of a Forest on the Effect of an Atomic Weapon.
5	U.S.N./Nav.Ord.L. NOLR.1169 (Home Office CD.6935)	Confidential U.K. Eyes Only	Base Surge Analysis - H.E. Tests.
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1	N.D.R.L. April, 1949 (AD-95H) Home Office CD.5957) M.O.D.Ref.No.70	Unclassified	An Estimate of the Relative Hazard of Beta and Gamma Radiation from Fission Products.
2	Knolls At. Power Lab. KAPL-559 TIB/AE/166	Unclassified	Evaluation of the Effects of an Atomic Bomb Detonation in the State of Nevada on Airborne Contamination at KAPL Site and Environs.
3	Knolls At. Power Lab. KAPL-1045.P.48793	Unclassified	Method for Evaluating the Radiation Hazard from a Nuclear Incident.
4	A.E.C. of Canada, Chalk River Report CREL.529 P.52388	Unclassified	Hazard due to Beta Radiation from Fission Products Deposited on the Ground After an Explosion.
5	USN/RDL Tech. Memo.18 P.50734	Unclassified	Estimation of the Gamma Dose Associated with Radioactive Fallout Material.
6	U.S.A. (MOD Note No.103)	Unclassified	Health Safety Problems and Weather Effects Associated with Atomic Explosions (Hearing of J.C. on A.E., Congress, U.S.A.)
7	Nat. Bureau of Standards Report 2224	Secret U.K. Eyes Only	Gamma Radiation in Air due to Cloud or Ground Contamination.
8	U.S. Fed.Civ.Def.Admin. Bulletin No. 178 (CD.7041 Home Office)	Unclassified	Radioactive Fallout from Nuclear Explosions
9	U.S.N./R.D.L. (DRB.55/3199)	Secret	The Nature of Individual Radioactive Particles I (Surface and Underground ABD Particles.

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10	USN/RDL (DRB.55/3198)	Secret	The Nature of Individual Radioactive Particles II.
11	USN/RDL (P.53340)	Confidential/ Discreet	Concenctration of Airborne Radioactivity Observed during Project 6.2 Field Experiments at Operation Jangle.
12	U.S.A.E.C.		Handbook on Air-cleaning, 1952.
13	U.S.A.A.F. Weather Service Manual 105-53 (Home Office CD.6617)	Unclassified	Radioactivity Fallout and Radex Plots (1952)
14	USN/RDL (CD.3660 Home Office)	Unclassified	Chemical Species of Elements from Atomic Bomb Detonation in Air.
15	1954 Tripartite Conference U.S.A. Section No. 2.	Confidential U.K. Eyes	Initial Gamma Radiation, Neutron Radiation Cloud Physics and Nuclear Shielding.
16	1954 Tripartite Conference U.S.A. Section No. 10	Confidential U.K. Eyes	Residual radiation, Fallout and Decay Laws
17	Bulletin of Atomic Scientists, Vol.XI No.7, September, 1955.	Unclassified	University of Chicago Reunion. Radioactive Fallout. Willard F. Libby.

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18	Operation Wigwam, Project 2.6 TIL Ref. P.60562	Secret/ Discreet	Mechanism and Extent of Early Dispersion of Radioactive Products in Water. Operation Wigwam, 1955. Folson and Isaacs.
19	Rand Corpn. Memo. RM-1676-AEC, 1956. CD.10479	Unclassified	A Catalogue of Fallout Patterns. Greenfield et al.
20	J. Res. Nat. Bureau Standards Vol. 58 No.2, Feb.1957 pp.101-109.	Unclassified	A High Speed Computor for Predicting Radioactive Fallout. Wright et al. N.B.S. Research Paper 2740.
21	Progress Report to Aug. 31st, 1955. TIL Ref. P.65414	Unclassified	Nature of Atmospheric Dust; Radioactive and Electron Microscope Measurements on Fallout on Princeton, N.J. October 21st, 1954 - August 10th, 1955. Heininger and Turkevich.
22	Air Force Cambridge Research Centre, 1951, WT-71, September, 1951. (M.O.D. Ref. No.139).	Secret	Operation Greenhouse. Scientific Directors Report, Annex 4.6. Atmospheric Conductivity and Fallout Particle Sizes. Cononiti et al.
23	NYO-4623	Official Use Only	Radiation Debris from Operation Castle on Islands of the Mid Pacific. Breslin and Cassidy.
24	A.E.C. Press Release January, 1956.	Unclassified	Radioactive Fallout and Radioactive Strontium. Speech by Dr. Willard F. Libby.
25	US Public Health Service Robt.H. Taft, Sanitary Eng.Centre, Cincinatti Ref.Indus & Eng.Chemistry 48-2 (Feb.6, 1956) P.251.	Unclassified	Radioactive Fallout in Surface Waters, Cetter and Goldin.

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26	Bulletin of Atomic Scientists, Vol.11, No. 9, November, 1955.	Unclassified	Global Fallout from Megaton Weapons. Ralph E. Lapp.
27	Knolls Atomic Power Lab. KAPL.1178 P.52924	Unclassified	Graphic Aids to Estimate Nuclear Radiation Hazards. Fitzgerald and Chappell.
28	Nucleonics, Vol.14, No.7 July, 1956	Unclassified	Data Sheet 14. Gamma-ray Scattering from Thin Scatterers.
29	U.S. Naval Research Lab. Report 4760. P.61167 ACSIL/55/3625	Unclassified	Radioactivity of the Air. Blifford et al.
30	U.S. Naval Research Lab. NRL Report 4607 P.60608 ACSIL/56/1441	Unclassified	Interim Report on the Relationship between the Air Concentration of Radioactive Fission Products and Fallout. (March-May, 1955). Blifford.
31	Sandia Corpn. 1957 Tripartite Conference Paper No. 2	Unclassified	Comments on Scaling of Neutron Flux with Altitude. Mehl.
32	Sandia Corpn., 1957 Tripartite Conference Paper No. 3	Unclassified	Analogue Computors for Fallout Prediction. Merritt.
33	A.F.S.W.P. 1957 Tripartite Conference Paper No. 18	Unclassified	Physical Aspects of Fallout. Shelton.

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35	U.S.N.R.D.L. Report WT-26 (deleted) (M.O.D.Ref. No.21).	Secret/Atomic	Operation Greenhouse. Scientific Director's Report, Annexe 6.5, Interpretation of Survey Meter Data (1951).
36	A.E.C. Oakridge, National Bureau of Standards. Extract of Report WT-329 (M.O.D.Ref.No.35)	Secret/Atomic	Operation Jangle, Project 2.1A. Gamma Radiation as a function of Time and Distance. Instrumentation Techniques.
37	National Bureau of Standards N.B.S. Circular 542 (M.O.D. Ref. No.45)	Unclassified	Graphs of the Compton Energy/Angle Relationship and the Klein Formula from 10 Kev to 500 Mev, 1953.
38	A.F.S.W.P. Report WT.351 (deleted) M.O.D.Ref.No.46.	Secret/Discreet	Operation Jangle, 1951, Project 2.1C-2. Aerial Survey of Local Contamination Terrain.
39	A.F.S.W.P. Report WT-395 (deleted) (M.O.D.Ref. No.47).	Secret/Atomic	Operation Jangle, 1951, Project 2.5A.2. Fallout Particle Studies.
40	A.E.C., Oakridge. Extract of Report WT-524 (M.O.D.Ref. No.48)	Secret/Atomic	Operation Snapper, Project 2.3, Neutron Flux Measurements. February, 1953. Part I. Au,S, and Ta. Part II. Proton Recoils in Nuclear Track Emulsions (O.N.R. Report). Part III. Fission Threshold Detectors.

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42	A.F.S.W.P. Report WT-348 (deleted) (M.O.D. Ref. No. 52)	Confidential/ Discreet	Operation Jangle, 1951, Project 2.4E, Gamma Ray Spectrum Measurements of Residual Radiation.
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44	A.B.C. Health and Safety Laboratory, New York, Operations Office, Instrument Branch Report NYO-4577. Revised August 12th, 1954 (M.O.D.Ref.84)	Unclassified	Mathematical Evaluation of Airborne Radiological Survey Data.
45	A.E.C., New York, Operations Office Report NYO.4505, January 12th, 1953 (M.O.D. Ref.85)	Secret/ Discreet	Radioactive Debris from Operations Tumbler and Snapper. Observations beyond 200 miles from the Test Site. Part I (see M.O.D. Ref. No. 145 for Part II of this Report).
46	A.E.C./U.S. Weather Bureau, Report N.Y.O.4512, 25th January, 1953 (M.O.D. Ref. No.145)	Secret/Atomic	Radioactive Debris from Operations Tumbler and Snapper. Observations beyond 200 miles from the Test Site. Part II.
49	U.S. Naval Ordnance Laboratory Report Nav.Ord. 2987, 1st May, 1954. A.F.S.W.P. Report 484 (M.O.D. Ref. No.86)	Confidential/ Discreet	The Scaling of Base Surge Phenomena of Shallow Underwater Explosions.

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52	N.R.L. Report NRL.4673 9th December, 1955 (M.O.D. Ref. No.185)	Unclassified	Monte Carlo Reactor Calculation.
53	N.R.L. Report NRL.4654 3rd November, 1955 (M. of D. Reference No.186)	Unclassified	Fallour Dosages at Washington. D.C. Blifford.
54	N.R.L. Report NRL.4695, 7th February, 1956. (M.O.D. Ref. No.197)	Discreet	Pseudo-Random Numbers and Collision Parameters for Monte Carlo Shielding Calculations.
55	N.R.L. Report NRL.4701 (M.O.D. Ref.198), 8th February, 1956.	Discreet	Gamma Ray Albedo from Iron.
56	U.S.A.E.C. Report LAV.56-4 (M.O.D. Ref. No. 204)	Unclassified	Operation Arme (Aerial Radiological Monitoring Exercise - October, 1955) Civil Defence Press Release.
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61	University of Illinois, Physics Department, Contract No. N6-ORI-071(01) (M.O.D. Reference No.239)	Unclassified	Nuclear Physics Final Report. March 1st, 1946 to March 31st, 1956. Lists Nuclear Physics Investigations and Reports issued thereon.
62	University of California Radiation Laboratory Report UCKL-4660(X) of 24th February, 1956 (M.O.D.Ref. No.248)	Secret/Atomic	Fallout ~~Field~~ YIELD Scaling. Computes Fraction of Fission Yield appearing as Fallout within 24 hours as a function of Fission and Fusion Yield, Height of Burst Tower and/or Device Masses and Surface Conditions. Theory and Measurements compared for Nevada and P.P.G. Shots.
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67	Scripps Institute of Oceanography, Report WT-1015, 17th December, 1956, (M.O.D. Reference No.34D)	Unclassified	Operation Wigwam, Project 2.6, Part II. Mechanism and Extent of the Dispersion of Fission Products by Oceanographic Processes, and Locating and Measuring Surface and Underwater Radioactive Contamination.
68	U.S.N.R.D.L. Report AD-145 Series D, (M.O.D.Ref.No.365)	Unclassified	Training Industrial Personnel in Radiological Safety (Lecture, August, 1949).
69	A.E.C. Health and Safety Laboratory, N.Y.Ops Office, Report NYO-4714, November, 1956, (M.O.D.Ref. No. 368)	Unclassified	Radiation Protection within a Standard Housing Structure.
70	Science, Vol.122, No.3181, p.1178, 1955.	Unclassified	Radioactive Fallout in the Marshall Islands.

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75	Nucleonics, Vol.15, No.4 pp.84-85.	Unclassified	Nucleonics Data Sheet No. 19, Induced Radiation. Radiation from Neutron Activated Slabs and Cylinders.
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79	Nucleonics, Vol.15, No.1, pp.52-53.	Unclassified	Nucleonics Data Sheet No. 18, Shielding. Gamma Attenuation with Build-up in Lead and Iron.

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81	American Society of Mechanical Engineers, 1955.	Unclassified	A Glossary of Terms in Nuclear Science and Technology.
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2	A.W.R.E. T36/57	Secret/Atomic	Operation 'Buffalo': The Gamma-ray Spectrum of Fallout from Buffalo Round 1.
3	A.W.R.E. TC 4/55	Secret	Air Currents above Ground Zero Area after a Low Burst, and their Relation to Fallout.
4	DAW Plans Note No.6	Secret/U.K. Eyes	An Analysis of the Pattern of Fallout.
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9	M. of Supply, AERE (1952) HP/R.879	Confidential	Distribution of Radioactive Material Produced in an Atomic Explosion.
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14	A.E.A., Windscale SWP/P16	Unclassified	Attenuation of Fission Product Gammas by Lead and Water.
15	J. of Appl. Phy. June, 1955 P.652	Unclassified	Monte Carlo Calculations on Gamma Ray Albedos of Concrete and Aluminium.
16	M. of Supply, AERE HP/M73	Restricted	Hazard of Fallout in the U.K. from Eniwetok H Bomb.
17	Home Office (S.A. Branch) (CD.5858)	Confidential	Gamma Radiation Dose Rates at Heights 3-3000 feet over Uniformly Contaminated Area
18	M. of Supply A.R.E. ARE/1/48	Secret	Physical Effects, Part 14. The Penetration of Isotopic Gamma Radiation through Plane Shield.

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GENERAL REFERENCES: Nuclear Radiation and Fallout from Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
19	M. of Supply, A.R.E. ARE/1/48	Secret	Physical Effects, Part 19. Shadow and Edge Effects on Gamma Ray Shielding.
20	M. of Supply, ARE/HER H13/51	Restricted	Tables for Solution of Gamma Ray Shielding Problems.
21	Physical Rev. 15th April, 1948	Unclassified	Penetration of Gamma through Thick Layers I. Plane Geometry, Klein Nishima Scattering II. Plane Geometry, Iron and Lead
22	M. of Supply, HER A28/52	Secret	Penetration of Gamma Radiation through the Walls of a Slit Trench
23	A.W.R.E. T53/54	Confidential	Penetration of Concrete Slabs by Gamma
24	A.W.R.E. T20/54	Confidential	Penetration of Gamma Flash into Anderson Shelters and Concrete Cublicles.
25	A.W.R.E. T104/54	O.U.O.	Prevention and Removal of Radioactive Contamination.
26	A.W.R.E. T85/54	Confidential	Collection of Samples for Radio-chemical Analysis.
27	A.W.R.E. T88/54	Secret	Collection of Radioactive Samples by Aircraft Sweeps.
28	A.W.R.E. T89/54	Secret/Atomic	Measurements of the Radioactivity of an Airborne Sample of the Cloud Collected at Broome, W. Australia.

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No.	Originator and Reference	Security Classification	Title
29	M. of Supply, C.D.E.E. Field Report 388 (DRB.54/12464)	Secret	Long Distance Travel of Particulate Clouds.
30	Tripartite Conference (9th) Porton (DRB.54/10275)	Restricted	Item 7. Radiological Defence. Aerial Survey of Fallout.
31	A.W.R.E. T113/54	Secret	Results of Aerial Radiological Survey over Australian Coastline between Onslow and Broome.
32	A.W.R.E. T3/55	Secret	Radiochemical Analysis of a Sample of Fallout from Monte Bello.
33	A.W.R.E. O-1/55	Secret	Use of Cobalt 60 in Radiological Warfare.

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GENERAL REFERENCES: Nuclear Radiation and Fallout from Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
34	A.W.R.E. E3/55	Secret/Discreet	Total Residual Gamma Dose from Randomly Distributed Ground Bursts of 5 megaton Thermonuclear Weapons.
35	A.W.R.E. Report T.50/57	Secret/Atomic	The Remote Measurement of the Variation with Time of Gamma Dose Rate from Fallout. Jones.
36	Nature, Vol.177 No.4517 p.990	Unclassified	Relationship between Air Concentration of Radioactive Fission Products and Fallout Following Operation Teapot. Blifford et al. U.S.N.R.L.
37	A.W.R.E. Report T-9/56	Secret/Atomic	Naval Radiological Measurements on Operation Totem. Final Report Part III. The Response of Fluorescent Glass Flash Gamma Dosimeters (Angular Gamma Distribution). Williams.
38	Home Office CD/SA No. 69, January, 1956	Unclassified	The Penetration of Gamma Radiation from a Uniform Contamination into Houses. McDonald.
39	A.W.R.E. Report O-35/36 (X)	Official Use Only	Dose Rates from Ground Contaminated with Residual Radioactive Material from an Atomic Explosion.
40	A.W.R.E. Report E-6/56	Secret/Atomic U.K. Eyes Only	The Dispersion of Radioactivity in the Sea after the Explosion of an Atomic Weapon (Operations Crossroads and Hurricane).
41	A.W.R.E. Report T-60/57	Secret	Operation Buffalo. Radioactivity Rates and Beta/Gamma Ratios in Atomic Bomb Clouds.

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GENERAL REFERENCES: Nuclear Radiation and Fallout from Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
42	Atomic Scientists Journal Vol.4, No.2, November, 1954, p.97.	Unclassified	Article by Prof. Yashushi Nishiwaki, of Osaka University School of Medicine Concerning Effects on Japanese Fishermen of the Fallout Following the American Test Explosion on 1st March, 1954.
43	A.W.R.E. Report T28/57	Confidential	Operation Buffalo: Measurements of the Radioactivity of Water Contaminated by Fallout.
44	A.W.R.E. Report T52/57	Confidential	Measurement of Airborne Radioactivity and Ground Contamination at 15 and 200 miles from Ground Zero.
45	A.W.R.E. Report T51/57	Secret	Operation Buffalo: The Aerial Survey of Radioactivity Deposited on the Ground.
46	A.W.R.E. Report T49/57	Secret	Operation Buffalo: The Radiation Survey of Ground Deposited Radioactivity.
47	A.W.R.E. Report T26/57	Confidential	Operation Buffalo: Measurements with Phosphate Glass and Quartz Fibre Dosimeters in the Field.
48	A.W.R.E. Report T40/57	Confidential	Operation Buffalo: The Measurement of Radiation Dose-rates from Fallout.

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No.	Originator and Reference	Security Classification	Title
49	1957 Tripartite Conference Report AWEC/P(57) 211	Secret/Atomic	Neutron-induced Activities in Soil.
50	1957 Tripartite Conference Report AWEC/P(57) 208	Secret/Atomic	On the Production and Interpretation of Fallout Patterns.
51	1957 Tripartite Conference Report AWEC/P(57) 202	Secret	Operation Mosaic II. The Fallout Analysed with Reference to H.M.S. Diana.
52	1957 Tripartite Conference Report AWEC/P(57) 201	Secret/Atomic	Operation Buffalo: Fallout Measurements.
53	1957 Tripartite Conference Report AWEC/P(57) 220	Confidential	Neutron Shielding Measurements from United Kingdom Trials.
54	1957 Tripartite Conference Report AWEC/P(57) 219	Secret	Naval Radiological Measurements on Operation Buffalo. Final Report, Part 1. The Polar Distribution of the Flash Gamma Radiation.
55	1957 Tripartite Conference Report AWEC/P(57) 215	Secret	The Protection Afforded by a Ship's Structure Against the Gamma Radiation Emitted by an Atomic Explosion.
56	1957 Tripartite Conference Report AWEC/P(57) 214	Confidential	Gamma Shielding Measurements from United Kingdom Trials.
57	1957 Tripartite Conference Report AWEC/P(57) 213	Secret/Atomic	On the Origin of the Initial Gamma Radiation.
58	Green, H.L. and Lane, W.R. (Spon, 1957)	Unclassified	Particulate Clouds, Dusts, Smokes and Mists (Book).

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No.	Originator and Reference	Security Classification	Title
59	Price, B.T. et al. Pergamon Press, 1957)	Unclassified	Radiation Shielding (Book)
60	A.W.R.E. Report T.59/57	Secret/Atomic U.K.Eyes Only	Neutron Measurements on Operation Buffalo.
61	A.W.R.E. Report, E.5/54	Secret/Atomic U.K.Eyes Only	Gamma Emission resulting from Radiative Capture of Neutrons by Nitrogen during an Atomic Explosion.
62	Home Office Report CD/SA85	Confidential	Attenuation and Scattering of Initial Nuclear Radiation.
63	A.E.R.E. Report HP/R.422	Unclassified	Gives an Estimation of the Lethal Dose of Neutrons.
64	Home Office Report CD/SA62 1955	Unclassified	Shielding from Residual Gamma Radiation.
65	Ministry of Supply H.E.R. Report H13/51	Restricted	Tables for the Solution of Gamma Ray Shielding Problems.
66	Home Office Report CD/SA68 1956	Confidential	Protection against Gamma Radiation from Fallout.
67	Home Office Publication. H.M.S.O. 1957	Unclassified	Assessment of the Protection afforded by Buildings against Gamma Radiation from Fallout.
68	Manual of Civil Defence, Vol.1, Pamphlet No. 2 (H.M.S.O.)	Restricted	Radioactive Fallout, a Provisional Scheme of Public Control.
69	C.D.E.E., Porton, Technical Paper 595, April, 1957.	Confidential	Filters for Fallout. Thomas.

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GENERAL REFERENCES: Nuclear Radiation and Fallout from Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
70	British Journal of Radiology, Vol.27, p.273 (1954)	Unclassified	Gives Estimate of the Lethal Dose of Neutrons. Cave.
71	British Standard 2597 (1955)	Unclassified	Glossary of Terms used in Radiology.
72	Draft British Standard CX(USM) 8230, September, 1957.	Unclassified	A Glossary of Terms used in Nuclear Science.
73	Proc.Roy.Soc. A.204,p.223, 1950.	Unclassified	Perpendicular Incidence of Radiation on a Plane Slab. Cave, Corner and Liston.
74	A.W.R.E. Report T.42/57	Secret/Atomic	Operation Buffalo. Attenuation and Scattering of Initial Nuclear Radiation.
75	Admiralty Research Laboratories Report ARL/RI/H2.44, April, 1957, (M.O.D.Ref. No. 320).		On the Optimum Tactics for evading Radioactive Fallout.
76	Home Office Report CD/SA87, December, 1957, (M.O.D.Ref. No.343).	Confidential/ Discreet	Some Recent Information from U.S.A. about Fallout from Ground Burst Megaton Weapons. (Gives Time of First Arrival and Duration of Fallout, and details of Upwind Contamination.)
77	Heitler, W., 1953.	Unclassified	Quantum Theory of Radiation (Book).
78	A.R.E. Report No. 3/54	Unclassified	Absorption of Gamma Radiation in Lead, Steel and Concrete.
79	A.O.R.G. Memo. C.12,	Secret/ U.K. Eyes Only	Report on a Visit to the U.S.A. to discuss recent Developments in Battle Area Surveillance (December, 1956).
80	A.W.R.E. Report H.12/52	Official Use Only	The Penetration of Gamma Radiation through the Walls of a Slit Trench.

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GENERAL REFERENCES: Nuclear Radiation and Fallout from Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
81	C.D.E.E. Porton Tech. Paper (R)15 4th March, 1959.	Restricted	Production of a Simulant for Radioactive Fallout.
82	A.W.R.E. Report T53/57	Secret U.K. Eyes Only	Operation Buffalo. Naval Radiological Measurements. Final Report Part 1. The Polar Distribution of the Flash Gamma Radiation.
83	Nature Vol. 182 (6th Sept. 1958) pp. 629-630	Unclassified	Deposition of Radioactivity in N.W. England from the Accident in Windscale. Chamberlain A.C.& Dunster H.J.
84	Nature Vol. 182 (Nov. 29th, 1958) pp. 1473-1478	Unclassified	Radioactivity Due to Fission Products in Biological Material. W.V. Mayneord. et al.
85	A.W.R.E. Report T59/57	S. Atomic U.K. Eyes Only	Operation Buffalo. Neutron Measurements.
86	A.W.R.E. Report E9/57	Secret/Atomic/ Discreet C.C.	On the Rise of an Atomic Cloud.
87	Home Office Scientific Adviser's Branch Report CD/SA.89 Oct.1958	Restricted	Survey of the Protection Afforded in Private Houses against Radiation from Fallout. D.T. Jones.
88	A.W.R.E. Report T34/58	Confidential	Gamma Dose-Distance Measurements at Operation Antler.
89	A.W.R.E. Report No. T37/58	Secret/Atomic U.K. Eyes Only	Operation Antler. The Shielding from Initial Radiation Afforded by Soil.
90	C.D.E.E. Porton Tech. Paper (R)20 9th April, 1959.	Confidential	Fallout Leaching Studies.

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No.	Originator and Reference	Security Classification	Title
91	War Office Operational Res. Unit - Far East. Report 2/58, November, 1958.	Secret	Attenuation of Gamma Radiation by Tropical Vegetation.
92	A.W.R.E. Report T53/58	Confidential	Operation Grapple-Y. Sampling of Radioactivity at Outlying Stations in the Pacific During April/May, 1958.
93	A.W.R.E. Report E2/58 DUPLICATES REF 98 REPORTS NOW O.U.O	Secret/Atomic Discreet	The Computation of Fallout Pattern, Part 2, Numerical Details. Vol.1. Text. Vol.2. Illustrations.
94	Nature Vol.182 (Sept.6th, 1958) pp. 627-8	Unclassified	Long Range Travel of the Radioactive Cloud From the Accident at Windscale. Steward N.G.L. Crooks R.N.
95	A.W.R.E. Report T44/58	Secret	Operation Antler. Radiological Survey Operation in the Alice Road Area.
96	A.W.R.E. Report O-7/58 January, 1959.	Secret/Atomic U.K. Eyes Only	Bibliography on Radiological Decontamination and on the Nature of Weapon Fallout. Ariss and Stevenson.
97	A.W.R.E. Report T34/58 October, 1958.	Confidential	Operation Antler. Gamma Dose-Distance Measurements.
98	A.W.R.E. Report E2/58. October, 1958	Secret/Atomic Discreet	The Computation of Fallout Patterns Part 2, Numerical Details. Volume 1, Text. Volume 2, Illustrations.
99	C.D.E.E. Porton Tech. Paper (R)11	Secret/ U.K. Eyes Only	Estimation of Ground Contamination and Airborne Concentration in Fallout. D.J. Thomas.
100	A.W.R.E. Report T37/58	Secret/Atomic U.K. Eyes Only	Operation Antler, Target Response Group. The Shielding from Initial Initial Radiation Afforded by Soil.
101	A.W.R.E. Report E1/58 E1/58	Official Use Only	The Computation of Fallout Patterns. Part 1 - General Theory.

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GENERAL REFERENCES: Nuclear Radiation and Fallout from Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
102	A.W.R.E. Report T42/57	Secret/Atomic U.K.Eyes Only	Operation Buffalo. Attenuation and Scattering of Initial Nuclear Radiations.
103	A.W.R.E. Report 0-7/58	Secret/Atomic U.K.Eyes Only	Bibliography on Radiological Decontamination and on the Nature of Weapon Fallout. (Details of over 200 References are given, including many brief abstracts)
104	13th Trip. Conf. on Tox. Warfare Paper TCR5/58	Confidential	The Attenuation of Residual Radiation by Structures. Collin and Western.
105	NWS Memo. 159/58 May, 1958	Confidential	Meteorology Aspects of Nuclear Explosions.
106	A.W.R.E. Report T48/57	Confidential	Operation Buffalo. The Penetration of Residual Gamma Radiation into Structures.
107	Res. & Dev. Branch U.K.A.E.A., Risley Report IGRL-IB/R-30 (1957)	Unclassified	Information Bibliography. Radiation Shielding.
108	12th Tri. Conf. on Tox. Warfare Paper TCR10/57	Confidential	Gamma-Ray Spectra of Residual Radiation from an Atomic Weapon. D.H. Peirson.
109	12th Tri. Conf. on Tox. Warfare Paper TCR8/57	Official Use Only	The Effect of Induced Activity in Soil on Dose-Rate from Fallout. G.C. Dale.
110	12th Tri. Conf. on Tox. Warfare Paper TCR3/57	Official Use Only	The Dose Rate Above an Extended Source - Aerial Survey K. Stewart.
111	ARL/N1/R862 June 1957	Confidential	Some Notes and Conclusions on Experiments Arising from the 1952 Montebello Trials with Particular Reference to the Fluid Fallout Hazard. C.A. Luxford.

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GENERAL REFERENCES: Nuclear Radiation and Fallout From Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
112	A.E.R.E. Report HP/M113 November, 1956	Unclassified	Isolation Distances Required for Radioactive Materials in Ships.
113	A.W.R.E. Theoretical Physics Note No. 27/57	Secret/Atomic U.K.Eyes Only	On the Prediction of Fallout Patterns. Beale.
114	Home Office Report CD/SA62 March, 1955	Restricted	The Effective Energy of Fission Product Gamma Radiation. C.B. Lax.
115	ARL/R3/C791 March, 1957	Secret/ Discreet	Operation Mosaic II. The Fallout Analysed with Reference to H.M.S. Diana. E.M.L. Beale.
116	A.W.R.E. Report T24/57	Secret/Atomic U.K.Eyes Only	Operation Mosaic. Theoretical Predictions.
117	A.W.R.E. Report TC1/56	Official Use Only	Estimation of the Energy Distribution of the Initial Gamma Radiation.
118	Home Office Report CD/SA79 August, 1956	Restricted	Developments in the U.K. In Relation to a Fallout Reporting Organisation. McDonald.
119	Home Office Report CD/SA80 November, 1956	Restricted	Condition of the Atmosphere when a C.D. Post is Sealed for Six Hours. McAulay and Collins.
120	Home Office Report CD/SA66 May, 1956	Confidential	A Proposed System of Radiological Control for Civil Defence Operations in an Area Devastated by a Nuclear Explosion. Stanbury

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GENERAL REFERENCES: Nuclear Radiation and Fallout from Nuclear Weapons

No.	Originator and Reference	Security Classification	Title
121	A.E.R.E. Report EL/R1555 November, 1954	Unclassified	The Gamma-Ray Spectrum of Fission Products from Slow Neutron Irradiation of Uranium 235.
122	A.E.R.E. Report EL/R1619 1955	Secret	The Gamma-Ray Spectra of Dust Samples from the American Nuclear Weapon Trial of 1954.
123	D.A.W. Plans Note No. 11 November, 1955	Restricted	Optimum Evacuation to Minimise Fallout Casulaties and the Irreducible Minimum Area of Effect. N. Simmons.
124	ARL/R1/R620 January, 1954	Restricted	The Attenuation of Cobalt 60 Gamma Radiation in a Spherically Symmetrical Water Medium, and Comparison with Results of Other Observers.
125	ARL/R1/R642 January, 1954	Secret	The Measurement of the Angular Distribution of Multiple Scattered Gamma Radiation from a Cobalt 60 Source in Air.
126	ARE Report 3/54	Unclassified	The Absorption of Gamma Radiation in Lead, Steel and Concrete.
127	Home Office Report CD/SA42 August, 1953	Confidential	Estimates of the Radioactive Contamination of Land Areas from an Adjacent Underwater Explosion.
128	Home Office Report CD/SA45 November, 1953	Confidential	Gamma Radiation Dose Rates at Heights of 3 to 3,000 ft. above a Uniformly Contaminated Area.

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No.	Originator and Reference	Security Classification	Title
129	AERE Report HP/R1782 1955	Official Use Only	The Shielding Provided by a Brick House Against the Gamma Radiation from a Uniformly Deposited Source. (Experiments with Cobalt 60).
130	AWRE Report 7/55	Secret	Operation Totem. Radiochemical Analysis - Neutron Flash.
131	HER Report H23/52	Restricted	A Comparison Between Experimental and Two Theoretical Methods for the Solution of Gamma Ray Penetration Problems.
132	HER Report H6/53	Restricted	The Angular Distribution of Multiply Scattered Gamma Radiation from a Point Source.
133	AWRE Report T8/55	Secret	Operation Totem. Fallout Particles from Rounds 1 and 2.
134	AWRE Report TC5/55	Secret	Variation of Dose Rate with Height Above the Fallout Area.
135	A.W.R.E. Report 0-62/58	Confidential	The Estimation of the Dose Due to a Radiation Burst From a Transient Super-critical Assembly.
136	Home Office Report CD/SA 94, May, 1959	Restricted	Up-wind Fallout from Megaton Explosions. Stanbury and Western.
137	Air Ministry Science 2. Memo 272 (1957)	Secret	The Effect of Radioactive Fallout on the Operation of Fighter Airfields.

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No.	Originator and Reference	Security Classification	Title
1	Defence Res. Board of Canada (Suffield Report 178) P47005		Studies with a Large Gamma-Ray Source distributed in the Open.
2	N.A.T.O. (CD.7232, Home Office)	Unclassified	Radiological Contamination
3	Kyoto University Bull. Inst. of Chemical Research	Unclassified	Radioactive Dust from the Nuclear Detonation, November, 1954.
4	Canada D.R. Board Suffield Tech.Paper 18 Summary (Home Office CD.6181)	Secret	A Study of Mixed Fission Product Contamination on Concrete and Earth Areas.
5	At.En. Canada, Report CREL-529, January, 1953 P.52388	Unclassified	Hazard due to Beta Radiation from Fission Products deposited in the Ground after an Atomic Explosion, Goulding and Cowper.
6	Arbeits Gemeinschaft Kernreactor, Switzerland Internal Report No. 3 March, 1954. TIB Translation T.4502	Unclassified	The Estimation of the Spreading of a Radicactive Gas Cloud in the Atmosphere in Various Weather Conditions. Erikson and Hälz.

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No.	Originator and Reference	Security Classification	Title
7	Japanese Society for the Promotion of Science, 1956. A.W.R.E. Library Ref. 16927	Unclassified	Research on the Effects and Influences of the Nuclear Bomb Test Explosions, Vols. 1 and 2.
8	Canadian Journal of Physics, Vol.29, p.1 (1951)	Unclassified	An Account of the Spectrum of the Gamma Radiation resulting from the Capture of Thermal Neutrons by Nitrogen. Kinsey et al.
9	Canadian Department of National Defence, O.R.G. Report 57/4, March, 1957, T.I.L.Ref.P.64516.	Restricted	Data for Planning Reception and Protection in British Columbia of the Maritime Provinces in a Nuclear War. Gives Estimates of the Percentages of the Population benefitting from Fortuitous Screening Factors of Various Sizes.
10	D.R.B. Canada, Suffield Experiment Station, Technical Note No.19, December, 1957. T.I.L. Ref. P.73101.	Unclassified	The Size Distribution of Radioactive Debris from Nuclear Weapons (Gives Variation of Mass Median Diameter from 23rd January to 26th November, 1957).
11	C.E.A.N. (France). Home Office Ref. CD.11135.	Unclassified	La Retombee Radioactive jusqu'au 1 October, 1957, includes Charts of Rainfall and Rainwater Activity 1955 to 1957.
12	French Civil Defence Authorities. Home Office Ref.11134.	Unclassified	(French) Civil Defence and the Problems of Accretion of Radioactivity in Flora and Fauna. Biofizike L.1, pp.68-75.

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No.	Originator and Reference	Security Classification	Title
13	1956, U.S.S.R. (D.S.I. Translation No.155.)	Unclassified	Protection from X-rays and Gamma Radiation. Explains Construction of a Nomogram. Bibergal and Margulis.

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No.	Originator and Reference	Security Classification	Title
1	U.S.Fed. Civil Defence Admin. Tech. Manual TM-13-3 (DRB.54/11658)	Unclassified	Clearance and Restoration of Streets and Highways in C.D. Emergencies.
2	U.S.A.E.C. Ref.TN-6000-5 1954, (M.O.D.Ref.No.81)	Unclassified	Contractors' Construction Standards for Buildings for the U.S.A.E.C. - Part 6300, Design Criteria.
3	A.E.C. Nevada Test Site, U.S. Government Printing Office, 1955, (M.O.D.Ref. No. 93)	Unclassified	Operation Cue. Atomic Test Programme, Nevada, April, 1955, for the Federal Civil Defence Administration.
4	A.F.S.W.P. Report No.805, August, 1954.	Confidential	Blast Pressure Requirements for Structural Damage. Newmark.
5	Rand Corporation Report RM.145, 20th April, 1949, (M.O.D.Ref.No.109)	Unclassified	Target Coverage. Germond.
6	F.C.D.A., (M.O.D.Ref.No. 124)	Unclassified	Federal Civil Defence Administration Annual Report, 1954.
7	Air Installations Division H.Q. Air Material Command, Wright-Patterson A.F.B., Dayton Report WT-88, May 1952,(M.O.D.Ref.No.131)	Secret/Atomic	Operation Greenhouse. Scientific Director's Report, Annexe 3.3, U.S. Air Force Structures. Appendix 1, Blast Loading and Response of Structures, Section 2, Structural Response.

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No.	Originator and Reference	Security Classification	Title
8	Armour Research Foundation Report on Nuclear Explosions 1951, M.I.T. Report of 15th July, 1951, (M.O.D. Ref.No. 132)	Confidential/ Atomic	Operation Greenhouse. Interim Report for Scientific Director's Report, Annexe 3.1, Vol.2, Army Structures Test Appendix 7, Permanent Effects.
9	Armour Research Foundation Report. (M.O.D.Ref.No.133)	Confidential/ Atomic	Operation Greenhouse. Interim Report. Scientific Director's Report, Annexe 3.3, Air Force Structures Test, Vol.3, Blast Loading and Response of Model Structures.
10	Armour Research Foundation Report. (M.O.D.Ref.No.134)	Confidential/ Atomic	Operation Greenhouse. Interim Report. Scientific Director's Report, Annexe 3.3, Air Force Structures Test, Vol. 4, Project 3.3, Appendix E, Vol.3, Blast Loading and Response of Prototype Structures and Quarter Scale Model.
11	Bureau of Naval Personnel Report Navpers 10097, U.S. Government Printing Office, 1955. (M.O.D.Ref.No.146).	Unclassified	U.S. Navy Training Courses - Atomic Warfare Defence.
12	M.I.T. Department of Aeronautical Engineering Paper AD.71541, (M.O.D.Ref. No.385)	Unclassified	The Combined Effects of High Intensity Heating and Dynamic Loading on a One Cell Box Beam. M.Sc. Thesis by F.L. Williams.

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No.	Originator and Reference	Security Classification	Title
1	Tripartite Conference on C.B. and R.W. 9th Porton (DRB.54/10123)	Secret	Service Aspects, Item 5. Protection against Atomic Attack by Dispersion of Ships and the Use of Smoke to Diffuse Thermal Effects. 21.7.54.
2	War Office, Operation Totem, 1953. Army Equipment Group	Secret	"Interim Summary of Trials Results prepared for D.A.W.R.E."
3	Tenth Tripartite Conference on Toxicological Warfare. A.E.R.E. EL/R.1798, p.46.	Secret	A report on the Meetings on Radiological Defence.
4	1957 Tripartite Conf. ARDE Report (B)46/57	Unclassified	An Approximate Solution of the One-dimensional Transport Equation.
5	Army Operational Research Group, A.O.R.G. Report No. 2/57. March, 1959.	Secret/Discreet/ U.K.Eyes Only	Optimum Burst Heights in the Tactical Use of Nuclear Weapons.
6	ARL/R4/C791 Sept. 1957	Secret	Operation Mosaic. Final Report on Naval Measurements.
7	Air Ministry Science 2. Memo 270 (1957)	Confidential	Target Coverage by a Number of Nuclear Weapons.

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No.	Originator and Reference	Security Classification	Title
1	Harvard University, Air Cleaning Laboratory NYO-1595	Unclassified	Blast Damage to Air Cleaning Devices. Progress Report July, 1953 to June, 1955. Billings, Dennis and Silverman.
2	American Machine and Foundry Co. Final Rep. Project MR.1013 Vol.1 TIL P.65454 Vol.2 TIL P.65455	 Secret/Discreet Unclassified	Transient Drag and its Effect on Structures. Final Report and Bibliography (Fully Detailed).
3	Ammann & Whitney. Report to Chief of Engineers, U.S.Army. DA-49-129-eng-120. 2 Vols. TIL. P.57300 and P.57301	Confidential	Design of Structures to resist Atomic Blast (Fully Detailed).
4	A.F.S.W.P.Report No.494, August, 1953.(M.O.D.Ref. 311).	Unclassified	The Effect of Long Positive Phased Blast Waves on Drag and Diffraction Type Targets. Newmark.
5	Technical Services (Research Memo.No.41,1954) (M.O.D.Ref.No.12).		Evaluation of Blast Effects on Structures.
6	U.S. Naval Ordnance Laboratory Report Navord 2451, 21st July, 1952, (M.O.D.Ref.No.87).	Confidential/ U.K.Eyes Only	The Optimum Height of Burst for High Explosives.

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No.	Originator and Reference	Security Classification	Title
7	A.F.S.W.P. Report ITR-1408 6th December, 1957, (M.O.D. Ref.No.378).	Confidential/ Discreet	Operation Plumbbob, Project 1.8b, Preliminary Report, Effects of Rough Terrain on Drag-Sensitive Targets.
8	Armour Research Foundation Project MO.24-1	Confidential/ Discreet	Final Report No. 18, 1954.
9	A.F.S.W.P. Report WT-1168	Official Use Only	Operation Teapot, Project 33.4. Distribution and Density of Missiles from Nuclear Explosions.
10	A.F.S.W.P. Report ITR-1469	Official Use Only	Operation Plumbbob, Project 33.3. Tertiary Effects of Blast-Displacement.

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DAMAGE TO TARGETS IN GENERAL : Blast

No.	Originator and Reference	Security Classification	Title
1	ARDE Report (B24/57)	Confidential/ Discreet	A Unified Theory of Damage from Minor External Blast. Thornhill.
2	ARDE Memo. (S18/57)	Secret/ U.K.Eyes Only	Models and Targets to be Employed in 'L' Lane on Operation Buffalo. Laing.
3	Proc.Roy.Soc.(A) Vol.1226 No.311. 20.8.57.	Unclassified	Studies in Collapse Analysis of Rigid/Plastic Plates with a Square Yield Diagram. Mansfield (Royal Aircraft Establishment).
4	"Nature", October, 1957 Vol. 180 No.4588, p.702	Unclassified	Aerodynamic Drag of Perforated Plates. Letter from Francis and Minton (Imperial College).
5	Home Office Civil Defence Structural Precautions Research Committee Paper CD/SPR/137 (1954)	Secret	Blockage of Roads and Open Spaces by Debris caused by a 20 KT Bomb.
6	A.W.R.E. Report E6/55	Secret/Atomic/ Discreet (C.C.)	Estimates of Some Blast Wind Effects of Megaton Bombs.
7	Nature, Vol.181, No.4613, p.873, 29th March, 1958	Unclassified	Damage to Solids by Liquid Impact at Supersonic Speeds. Bowden and Brunton.
8	Armament Research & Dev. Estab. A.R.D.E. Memo. 29/59	Confidential	Models and Target Response Scaling Laws. G.J. Laing.
9	AORG Memo. F.15 Oct. 1955	Secret	Protection Afforded by Terrain Against the Effects of Nuclear Explosions.

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No.	Originator and Reference	Security Classification	Title
1	Civil Experiment Station, Canada, Report D.89-16-01-12, 25th April, 1958, T.I.L. Ref.P.71632.	Unclassified	The Use of Models in the Study of the Blast Effects of Simulated Nuclear Weapons. Jones, G.H.S. (the above has also been published as Suffield Technical Paper No. 132 of 1958).

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DAMAGE TO TARGETS IN GENERAL: Thermal Radiation Damage and Fire Storms

No.	Originator and Reference	Security Classification	Title
1	U.S.A.Department of Agriculture Report AFSWP-413. Home Office Ref. CD.7384. (M.O.D.Ref. No.26).	Unclassified	Primary Ignitions following Atomic Attack on Urban Targets (Transient Exterior Fuels. 1953).
2	U.S.A. Department of Agriculture, Report AFSWP-412. Home Office Ref. CD.7385. (M.O.D.Ref. No.28).	Unclassified	Distribution of Primary Ignition Points following Attack on Urban Targets. (Transient Exterior Fuels. 1953).
3	U.S. Naval Radiological Defence Laboratory Paper No. 14 for 1957 Tripartite Conference.	Unclassified	Ignition of Combustible Materials. Plum.
4	U.S. Forest Services. (M.O.D.Ref. No. 24)	Unclassified	Fire - Progress Report No. 2 (1954). A Study of Mass-Fire Build-up.
5	U.S. Forest Services. (M.O.D.Ref. No.25)	Unclassified	Fire. Progress Report No. 1, 1954.
6	U.S. Department of Agriculture, 20th January 1952, (M.O.D. Ref.No.94).	Confidential/ Discreet	Burning Potential - Forest and Wild Land Areas. Department of Fire Research Report to O.R.O. Johns Hopkins University.
7	A.F.S.W.P. Report WT-774 (M.O.D.Ref.No.77).	Confidential/ Atomic	Operation Upshot-Knothole, Project 8.11A, Incendiary Effects of Building and Interior Kindling Fuels, 1953.

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DAMAGE TO TARGETS IN GENERAL: Thermal Radiation Damage and Fire Storms

No.	Originator and Reference	Security Classification	Title
8	U.S. Department of Agriculture Forest Service Forest Products Laboratory Wisconsin. Manual AFSWP-700	Confidential/ Atomic	Thermal Data Handbook - Sanitized Edition.
9	U.S.N.R.D.L.Report TR-101, 11th August,1955, T.I.L. Reference P.67803. Acsil Ref.57/3418.	Unclassified	Thermal Vulnerability of Military Installations.

DAMAGE TO TARGETS IN GENERAL: Thermal Radiation Damage and Fire Storms

No.	Originator and Reference	Security Classification	Title
1	S.A. Br. Home Office CD/SA6 (CD/3090)	Secret	The Atomic Bomb as A Fire Raiser. A study of the Mechanism of Initiation and Development.
2	M. of Supply, A.R.D.E. BM/B/1/2/55	Confidential	The Theory of Thermal Explosions: the Initiation of Explosion by High Intensity Thermal Radiation.
3	S.A.Home Office CD.1628	Secret	Some thoughts on the Fire Problem from Atomic Bombs.
4	S.A.Home Office CD/SA10 CD.2176	Secret	The Fire Risk Attendant on the Use of Black-out Curtains during an Atomic Bomb Attack.
5	Min. of Home Security REN.567 (CD.2952A)	Restricted	Investigation of Fire Damage Caused by Atomic Bombs at Nagasaki and Hiroshima (Jan.1950).
6	Tripartite Conference on C.B. and R.W. 9th Porton (DRB.54/10123)	Secret	Service Aspects, Item 5. Protection against Atomic Attack by Dispersion of Ships and the use of Smoke to Diffuse Thermal Effects.
7	DSIR/FOC Joint Fire Res. Orgn.Special Report No.2 (CD 6076)	Unclassified	Heat Transfer by Radiation (1953).
8	Joint Fire Research Organisation, S.R.Note 28/1956	Confidential	Heat Radiation Shelters for Defence against Atomic Explosions. Simms, Hinkley and Weston.
9	A.R.E. Report 1/48 Pt.20	Secret	The Physical Effects of Atomic Bombs. The Risk of Fires from Fractured Oil Tanks and Pipe Lines by Radiation Heating from an Atomic Bomb.

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DAMAGE TO TARGETS IN GENERAL: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	U.S. Chem.Corps CRLR.326 (CD.7081)	Confidential/ Discreet	Interim Report. Experimental-theoretical Attenuation of 1.2 Mev Gamma Radiation by Simple Structures.
2	U.S. Chem. Corps. Chem. & Rad. Lab. Report TCIR.591 DRB.54/13139	Unclassified	Total Linear Absorption Coefficients of Various Types of Media for Gamma Radiation.
3	U.S. Rand. Corp. Rep.240 (DRB.54/5142)	Unclassified	Gamma Ray Transmission through Finite Slabs.
4	U.S. At.En. Comm. TID.3032 (DRB.54/4505)	Unclassified	Radiation Shields and Shielding. Bibliography of Unclassified A.E.C. Rept. Literature.
5	U.S. Dugway Proving Ground (DRB.5497)	Confidential	ETD Annual Environment Evaluation Report, 1953. 1st Report of 4-year Programme to Determine Capabilities of CW, BW and RW under Adverse Desert and Tropic Conditions.
6	U.S. Army Chemical Centre 1957 Tripartite Confer. Paper No.7	Confidential/ Atomic	Neutron and Gamma Shielding and Induced Activity. Tompkins.
7	U.S.A.E.C. 1950, U.S. Government Printing Office.(M.O.D.Ref.No.9)	Unclassified	Control of Radiation Hazards in the Atomic Energy Programmes.
8	U.S.A.E.C. Report NYO-3075 by Nuclear Developments Associates (M.O.D.Ref.No.14)	Unclassified	Calculations of the Penetration of Gamma Rays. Detailed Report (196 pages) Goldstein and Wilkins, 30th June, 1954.

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DAMAGE TO TARGETS IN GENERAL: Nuclear Radiation. Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
9	Chemical Corps Chemical and Radiological Laboratories Report CRLR-326, 15th September, 1955,(M.O.D.Ref.No.82).	Confidential/ Discreet (C.C.)	Experimental-Theoretical Attenuation of 1.2 Mev. Gamma Radiation by Simple Structures.
10	Chemical Corps Chemical and Radiological Laboratories Report CRLR-297, 1st August, 1953, (M.O.D.Ref.No.83).	Confidential/ Discreet (C.C.)	Attenuation of 1.2 Mev. Gamma Radiation by Soviet and U.S. Military Vehicles and U.S. Rail Equipment.
11	Naval Research Laboratories Report NRL 4581 of 26th July, 1955 (M.O.D.Ref.No.149)	Discreet	Penetration of Na 24 Radiation through H_2O and Hg.
12	National Bureau of Standards Report NBS.2902 of 8th October, 1954 (M.O.D.Ref.No.152)	Unclassified	The Dose received by Partially Shielded Gamma Ray Detectors.
13	Naval Research Laboratory Report NRL-4666, 7th December, 1955 (M.O.D. Ref. No. 183).	Unclassified	Total Cross Sections for 14 Mev. Neutrons, and Comparison of Measured Values with Values calculated from the Complex Square-Well Model.

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DAMAGE TO TARGETS IN GENERAL : Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
14	U.S.N.R.D.L. Report TR-31 (Contract NY-320-001), 14th January, 1955 (M.O.D.Ref.No.362).	Unclassified	Buffer Zones required in the reclamation of Radiologically Contaminated Areas.
15	U.S.N.R.D.L. Report AD-322 (March, 1952) (M.O.D.Ref.No.364)	Unclassified	Report of Land Reclamation Tests.
16	A.F.S.W.P. Report No. WT-400	Confidential	Operation Jangle, Project 6.2, Protection and Decontamination of Land Targets and Vehicles.
17	Tech. Command Interim Report No. 627 Project 4-12-07-001 Feb. 1951	Confidential	The Proper Role of Detergents in Relation to Radiological Decontamination. Levin.
18	U.S. Society of Mech.Eng. Report 57-SA-52 June 1957	Unclassified	An Engineering Approach to Radiological Decontamination. M.B. Hawkins.
19	USN/RDL Report AD-220(T) May 1950	Unclassified	Field Factors Affecting Contamination. Stetson et al.

No.	Originator and Reference	Security Classification	Title
1	Tenth Tripartite Conf. on Toxicological Warfare A.E.R.E. EL/R.1798, p.46	Secret	A Report on the Meetings on Radiological Defence.
2	R.A.E. Library Bibliography No. 195.	Unclassified	List of (Unclassified) References on Atomic, Photon, and Ion Propulsion of Aircraft; the Shielding of Aircraft Nuclear Reactors; the Medical Hazards of Atomic Powered Aircraft; and the Effect of Atomic Radiation on Aircraft Materials and Components.
3	1957 Tripartite Conf. A.W.R.E. Report 0-35/56(X)	Official Use Only	Dose rates from Ground Contaminated with Residual Radioactive Materials from an Atomic Explosion.
4	A.W.R.E. Report 0.49/55	Official Use Only	A Guide to Radiological Decontamination after a Nuclear Explosion or Radiological Attack.
5	A.W.R.E. Report T.22/57	Confidential	Operation Buffalo. Decontamination Group Report, Parts 1-4.
6	C.D.E.E. Porton Tech. Paper (R)15, Sept. 1958.	Restricted	Radiological Decontamination: an Investigation of the Absorption of Fission Isotopes into Concrete. H. Stretch.

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PERSONNEL, ANIMALS, AND VEGETATION: Damage by Combined Effects.

No.	Originator and Reference	Security Classification	Title
1	B.N.M.L.O. Washington /3 13th Aug. 1954	Restricted U.K. Eyes Only	Medical Aspects of Atomic Warfare.
2	Tufts College. Inst. for App.Exp.Psychology and U.S.N. Special Devices Centre. Nav Eos P-643 ACSIL/50/1938 TIB No. P.50584	Unclassified	Handbook of Human Engineering Data, 2nd Edition (Revised), 1.11.1952.
3	Operations Res. Office Report ORO-T-1 (Conarc). CORG-FER-1 (M.O.D.Ref. Nos. 265 and 266)	Secret/Atomic	Vulnerability of The Infantry Rifle Co. to the Effects of Atomic Weapons: (A study of a week's Infantry manoeuvres). Parts I and II.
4	A.F.S.W.P. Report 602 (M.O.D. Ref. No. 115)	Secret/Discreet	A Study of the Influence of a Forest on the Effects of an Atomic Weapon (1953).
5	Department of Forest Fire Research. Letter dated 13th July, 1954. (M.O.D. Ref. No. 116)	Confidential/ Discreet	Letter from U.S. Department of Agriculture to A.F.S.W.P. forwarding the draft Isodamage Curves for three types of Forest Stand, for use in "Capabilities of Atomic Weapons".
6	U.S.A.E.C. Paper Wash. 545, 1955 (M.O.D.Ref.Nos. 144 and 191)		Tripartite Discussions on Effects of Atomic Weapons on Human Beings and their Environment, 14th April, 1955. Subjects include Effects of Induced Radiation, Pressures, Times to Minimum, Cratering, Burns, and the Effects of Fallout on Certain Marshallese Islanders.

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PERSONNEL, ANIMALS AND VEGETATION: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
7	British Naval and Army Medical Liaison Officer, Bureau of Medicine and Surgery, Washington. BNAMLO/19, 14th September, 1956 (M.O.D.Ref.No. 240)	Unclassified	Management of Mass Casualties. Report of $5\frac{1}{2}$ day Course at Walter Reed Army Institute for Research, 20th-25th August, 1956.
8	U.S. Government Printing Office, 1956.	Unclassified	Medical Effects of Atomic Bombs in Japan. Oughterson and Warren.
9	Tripartite Conference, 1954.	Secret/ U.K.Eyes Only	Biological Effects of Atomic Weapons.
10	J.Amer.Med.Assoc., Vol.34, pp.1143-8, 1947	Unclassified	Medical Sequelae of Atomic Bomb Explosions. Le Ray.
11	J.Amer.Med.Assoc., Vol. 147, pp.858-862, October, 1951.	Unclassified	Nature of Air Raid Casualties. Enloc.
12	J. Maine Med. Assoc., Vol.41, pp.144-159(1950).	Unclassified	What Every Doctor should know: Medical Aspects of Atomic Weapons.
13	Med. Clinics, N.Amer., Vol.36, pp.263-272 (1952) (Available in M.R.C. Library).	Unclassified	The Physician in Atomic Defence. Sears.
14	U.S.F.C.D.A.	Unclassified	Civil Befence Reading List.

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PERSONNEL, ANIMALS AND VEGETATION: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	Home Office (CD.9582)	Secret/U.K. Eyes	Casualty Rates for Ground Burst 10 Megaton Bombs, October, 1956.
2	A.W.R.E. T18/57	Confidential	Operation Buffalo: Target Response, Interim Report, Biology Group.
3	A.W.R.E. T18/54	Official use only	Hurricane Part 43. Trial carried out for Ministry of Food.
4	A.W.R.E. T44/54	Confidential	Summary Report on Biological Experiments.
5	D.T.S.D. Admiralty Part III of "Atomic Bomb Trials" (Op.Crossroads) CD.2122.	Top Secret	Biological Effects in the Bikini Atomic Bomb Trials.
6	A.O.R.G. Memo E.1.		Ready Reckoner for Atomic Casualties.
7	B.A.O.R. Operational Research Section Report 3/56.	Confidential	Effects of Atomic Weapons on Forests in North West Europe.
8	A .O.R.G. Report No.12/55	Secret/U.K. Eyes Only	The Protective Value to Personnel of Slit Trenches against Thermal and Gamma Radiation Effects of Nuclear Explosions.
9	Nelson, 1949.	Unclassified	Atomic Medicine. Behrens (Book)
10	Admiralty, 1955.	Unclassified	Course on Atomic Energy for Medical Officers
11	Home Office, H.M.S.O.	Unclassified	The H Bomb (Pamphlet).
12	War Office Code No. 11934 26/Manuals/3859 April, 1957.	Restricted	Notes on Nuclear Warfare for Medical Officers

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No.	Originator and Reference	Security Classification	Title
13	Army Operational Research Group A.O.R.G. Report No. 6/57	Secret	Mortality Rates from Nuclear Weapon Attacks. Hand N. E., Strong E. D., and Heritage K. J.

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PERSONNEL, ANIMALS AND VEGETATION: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	Australian A.O.R.G. Memo M.1		Effects on Infantry

PERSONNEL, ANIMALS, AND VEGETATION: Blast

No.	Originator and Reference	Security Classification	Title
1	Lovelace Foundation for Medical Education and Research, Albuquerque New Mexico TID.5251 (M.O.D. Ref. No. 301)	Confidential/ Atomic	The Biological Effects of Blast. A Critical Review, September, 1954. Clayton S. White.
2	U.S. Army Chemical Centre 1957 Tripartite Conf. Paper No. 10. A .W.E.C. P.57/49.	Unclassified	Blast Biology, Carl M. Herget.
3	C.E.T.G. Operation Teapot, Project 33-2 Report ITR-1180 (M.O.D. Ref. No. 296)	Confidential Atomic/ Restricted Data	Deals with Noise as a Factor in Harm to Animals in Shelters
4	U.S.D.A. Special Co-operative Project, Berkeley, California TM.54-2	Unclassified	Breakage Prediction for Longleaf Pine, Sandhill Area, Fort Benning.
5	Civil Effects Test Group Report ITR-1168.	Confidential/ Atomic	Operation Teapot, 1955, Project 33.4, Distribution and Density of Missiles from Nuclear Explosions.
6	J.Amer.Med.Assoc., Vol. 147, pp.1658-1663, December, 1951.	Unclassified	Atomic Bomb Injury - Mechanical. Simeare.
7	F.C.D.A.	Unclassified	The Impact of Air Attacks in World War 2. Physical Damage to Persons.

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PERSONNEL, ANIMALS, AND VEGETATION: Blast

No.	Originator and Reference	Security Classification	Title
8	A.F.S.W.P. Report WT-1197	Official Use Only	Operation Teapot, Project 39.43, Technical Photography (High Speed Blast Biology).
9	A.F.S.W.P. Report WT-1180	Official Use Only	Operation Teapot, Project 33.2, Effects of Noise in Blast - Resistant Shelters.
10	A.F.S.W.P. Report WT-1179	Official Use Only	Operation Teapot, Project 33.1. Biological Effects of Pressure Phenomena occurring inside Protective Shelters following Nuclear Detonation.
11	A.F.S.W.P. Report ITR-1507	Official Use Only	Operation Plumbbob, Project 33.6. The Internal Environment of Underground Structures subject to Nuclear Blast. II. Effects on Mice located in Heavy Concret Shelters.
12	U.S.F.C.D.A. TB-13-4	Unclassified	Civil Defence Technical Bulletin. Report on Identity Tags exposed to Blast.
13	A.F.S.W.P. Report ITR-1447 (Home Office Ref. 11189)	Official Use Only	Operation Plumbbob, Project 33.5. The Internal Environment of Underground Shelters subjected to Nuclear Blast. I. The Occurrence of Dust.

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PERSONNEL, ANIMALS AND VEGETATION: Blast

No.	Originator and Reference	Security Classification	Title
1	1957 Tripartite Conference Paper No. B(57)38. A.W.R.E. Paper TC.5/57	Confidential	Recent Observations on the Effects of Blast on Animals. Zuckerman.
2	Royal Naval Personnel Ctee. List of Classified Reports TIL/BIB(U)/12	Secret	Summary of Reports Dealing with Blast Effects on Submerged Men and Animals.
3	Textbook of Air Armament Part 2, Chap. 12, Ref. CB.04512B, SD.642.B.	Secret/Discreet	Chapter 12, Vulnerability of Human Targets to Fragmenting and Blast Weapons.
4	1957 Tripartite Conference Paper No. AWEC/P(57)40	Secret	A Field Study of the Displacement of Men by the Blast Wave from an Atomic Explosion.
5	1957 Tripartite Conference Paper No. AWEC/P(57)39	Confidential	Investigation to Assess Hazards from Flying Glass. Butterfield.
6	1957 Tripartite Conference R.N. Physiology Lab. Paper AWEC/P(57)37.	Confidential	Review of Underwater Blast Physiology. Wright.
7	CHABA-3 (Acsil 55/4958)	Unclassified	Effect of Blast Phenomena on Man. Eldredge.
8	A.R.E. Report 1/48, Part VI.	Confidential	Kinematic Effect of Blast on Man in the Open. Liston.
9	Ministry of Home Security Reports RC.108 and RC.376	Unclassified	Blast Effects on Lungs
10	Ministry of Home Security Report RC.249	Unclassified	Blast Effects on Heart and Head

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No.	Originator and Reference	Security Classification	Title
11	Ministry of Home Security Report RC.284.		Lethal Effects and Body Size
12	A.W.R.E. Report T3/58	Confidential	Operation Buffalo. Physiological Effects of Long Duration Blast Waves. Krohn and McGregor.
13	A.W.R.E. Report T2/59	Confidential	Operation Buffalo. Biology Group. Part 3.A. The Effects of Blast on Dummy Men Exposed in the Open.

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PERSONNEL, ANIMALS, AND VEGETATION: Thermal Radiation, Burns, Flash Blindness

No.	Originator and Reference	Security Classification	Title
1	U.S.N. Res. and Dev.Div. Bureau of Supplies and Accounts. SRI Project 872.	Secret	The Economics of Protective Clothing for Naval Personnel as a defence against Thermal Effects of Atomic Weapons
2	U.S. Univ. of Rochester U.R.254 CD.6054 P.44607	Unclassified	Thermal Burns from Atomic Bombs. Pearce & Kingsley, 1953. Also published in "Surgery, etc." April 1954, Vol. 98, pp.385-394.
3	U.S. Univ. of Rochester U.R.217	Unclassified	Study of Flash burns. Relation of Time and Intensity of Applied Thermal Energy to the Severity of Burns.
4	U.S. Univ. of Rochester Report UR-261	Unclassified	Study of Flash burns. Protection by 2, 4 and 6-layer fabric combinations.
5	U.S.A. Med. Res. and Dev. Bd. (DRB 54/6119)	Unclassified	A Study of the Physical Basis of Burn Production with Applications to the Defensive Reactions to an Atomic Bomb Air-burst.
6	USAF School of Aviation Medicine ORO.4750. Op. Buster, Project 4.3 (M.O.S. Ref. No. 165)	Confidential U.K, Eyes Only	Flash Blindness. Operation Buster, Project 4.3. Col. V.A. Byrnes.
7	USAF/SOAM UKP 36/1953 Op. Upshot-Knothole (M.O.D. Ref. No. 56)	Confidential U.K. Eyes Only	Flash Blindness.
8	USAF/SOAM UKP 36/1953 Op. Upshot-Knothole	Unclassified	Chorio-retinal Burns produced by an Atomic Flash
9	U.S.A.F./S.O.A.M.	Unclassified	Retinal Burns - New Hazard of the Atomic Bomb

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No.	Originator and Reference	Security Classification	Title
10	B.N.M.L.O. Washington /.3 13th August, 1954	Restricted U.K. Eyes Only	Medical Aspects of Atomic Warfare (includes comments on above Paper)
11	John Hopkins University ORO-T-115 ACSIL/52/1396	Restricted/ Discreet	The Effect of Atomic Explosions in Causing Temporary Blindness
12	U.S.N. N.Y. Naval Ship-yard. Ann. Report of Material Lab. p.66, 1954 ACSIL/55/2135	Unclassified	Improvement of Eye Protective Equipment.
13	10th Tripartite Conf. on Toxicological Warfare Sept. 1955, US Chemical Corps. R & E. Cmd. Prog. Rept.	Confidential	Eye Protection.
14	10th Tripartite Conf. on Toxicological Warfare Sept. 1955, Canadian Paper	Confidential	The need for Eyeshields which will combine Protection against both CW Agents and Thermal Radiation.
15	10th Tripartite Conf. on Toxicological Warfare September, 1955. U.S. Paper to Joint Meeting 5	Confidential	Protection of Eyes and Face against Thermal Radiation.
16	10th Tripartite Conf. on Toxiocological Warfare September, 1955. DCRL Canada Paper to Joint Meeting 5	Secret	Eye Protection.

PERSONNEL, ANIMALS AND VEGETATION: Thermal Radiation, Burns, Flash Blindness

No.	Originator and Reference	Security Classification	Title
17	10th Tripartite Conf. on Toxicological Warfare, September, 1955. Canadian Ann. Summary Report on Radiological Defence, p.1	Secret	Eye Protection
18	Proc. Am. Soc. Arts and Science, Vol.51 (1916) p.630	Unclassified	Article by Verhoeff and Bell, on Flashblindness.
19	U.S. Dept. of Army Quartermaster, R & E Command C3PRD-1 TPA No. P51200(1)	Confidential	Classified Supplement Annual Project Progress Report 1st January/ 31st December, 1954.
20	U.S.A.F. War Office, Library Ref. 623454. 91617 7, 1953	Confidential	Protection of the Eye Against Damage by Atomic Explosion.
21	Ohio States University Rés. Foundation. Armed Forces/N.R.C. Vision Cttee. Secretariat, 1953	Unclassified	Effects of Flashes of Light on Night Visual Acuity.
22	A.F.S.W.P. Report WT-506 (M.O.D. Ref. No. 323)	Confidential/ Atomic	Operation Snapper, 1952, Project 8.1. Effects of Atomic Bomb Explosions on Various Fuels
23	U.S. Navy Material Lab. Reports, Proj.5046-3		Part 39, May, 1954. The Temperature Rise of a Physical Skin Simulant behind an Irradiated Cloth Barrier. Part 42, Dec. 1954. The use of Polyethelene as a Physical Measuring System, for Evaluating Physiological Burns behind Fabrics.

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PERSONNEL, ANIMALS, AND VEGETATION: Thermal Radiation, Burns, Flash Blindness

No.	Originator and Reference	Security Classification	Title
24	Johns Hopkins University ORO-T-1	Secret/Atomic	Thermal Screening by Foliage is described in Report 3 of Section 3.1 page A.1.
25	Evans Research and Dev. Corpn. Final Report on Dept. of the Army Contract DA 19-129-QM-382, May, 1955 to June, 1956.	Unclassified	Development of a Foam Product for Protection against Thermal Effects.
26	J. Soc. Motion Picture & T.V. Engineers, Vol.60, No. 5, p.553, May, 1953.	Unclassified	Reflectance of Human Flesh (Skin). Stimson and Fee.
27	J. Appl. Physiology Vol.8, No.2, p.212, September, 1955	Unclassified	Spectral Reflectance of Human Skin in the Region 235/700 microns. Jacquez, et al.
28	A.F.S.W.P. 1957 Tripartite Conf. Paper No. 16	Unclassified	Flash Blindness and Retinal Burns, Bach.
29	A.F.S.W.P. 1957 Tripartite Conf. Paper No. 17	Unclassified	Skin Burns. Bach.
30	Division of Fire Research Forest Services, U.S. Department of Agriculture Report AFSWP-404, (M.O.D. Ref. No. 27.)	Unclassified	Thermal Properties of Forest Fuels (1952).

No.	Originator and Reference	Security Classification	Title
31	A.E.C. Report WT-6, (M.O.D. No. 190)	Secret/Atomic	Operation Greenhouse. Scientific Director's Report - Radiobiological and Flash Burn Data. Part VII - Swine. Part VIII - Dogs. Part IX - Thermal Burns.
32	A.F.S.W.P. -845 Materials Laboratory, (M.O.D. Ref. No. 75)	Unclassified	Method to Improve Optical Characteristics of the Black Polythene Skin Simulant. Project. NS081-001, 25th March, 1955.
33	University of Rochester Report UR-387, 29th March, 1959. (M.O.D. Ref. No. 99)	Unclassified	Thermal Protectivity of a Light Poncho Material (Vinyl coated Nylon).
34	University of Rochester Report UR-488, 29th May, 1957, (M.O.D. Ref. No. 360) T.I.L. Ref. P.66015.	Unclassified	Some Effects of Thickness of the Layer in Protection against Flash Burns by Creams.
35	University of Rochester Report UR-489, 5th June 1957. (M.O.D. Ref. No. 361)	Unclassified	Protection from Radiant Thermal Energy by Fabrics used as a Shield.
36	University of Rochester Report No. UR-354, T.I.L. Ref. P.50377.	Unclassified	Protective Qualities of Fabric expressed by a Protective Index.
37	University of Rochester Report No. UR-355, T.I.L. Ref. No. P.50376	Unclassified	Influence of Exposure Time and Irradiance on the Thermal Protective Qualities of Two-Fabric Assemblies

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No.	Originator and Reference	Security Classification	Title
38	Surgery, 1955, Vol. 37, p. 280.	Unclassified	Flash Burn Studies on Human Volunteers. Evans et al.
39	Surgery, Gyn. Obst. 1952, Vol. 94, p. 317.	Unclassified	Studies on Flash Burns: Threshold Burns. Morton et al.
40	New England Journal of Medicine, 1949, Vol. 241, p. 647.	Unclassified	Medical Progress: Mechanical and Thermal Injury from the Atomic Bomb. Pearse and Payne.
41	Journal of Applied Physiology, 1952, Vol. 4, p. 800.	Unclassified	Spectral Reflectance of White and Negro Skin between 440 and 1,000 Microns. Kuppenheim and Heer.
42	A.M.A. Arch. Opth. 1955, Vol. 53, p. 351.	Unclassified	Burns on the Retina. Byrnes, Brown, Rose and Cibis.
43	University of Rochester Report UR-79	Unclassified	Experimental Studies of Flash Burns. Also published in Arch. Path. 49, pp. 267-277, 1950.
44	University of Rochester Report UR. 226.	Unclassified	Flash Burn Studies: Carbon Arc Source.
45	University of Rochester Report UR-174.	Unclassified	Studies of Flash Burns. Quarterly Technical Report dated 31st July, 1951.
46	University of Rochester Report UR-338	Unclassified	Studies of Flash Burns. Influence of Skin Temperature on Cutaneous Burns in Swine.

No.	Originator and Reference	Security Classification	Title
47	University of Rochester Report UR-260.	Unclassified	Quarterly Technical Report dated 29th May, 1953.
48	O.S.R.D. Division 9, 1946.	Secret	Production of Casualties by Exposure to Heat. (Chapter 17 of Vol.1 of War Chemistry, Parts I and II).
49	A.E.C. Press Release. 23rd September, 1954.	Unclassified	Lecture to Seventh Annual Industrial Health Conference by J.C. Burgher. Describes Nature of Burns of Grades 1-5 and gives Calorie Dose required within 0.3 seconds as: Grade 1 - 2.3 " 2 - 4.5 " 3 - 7.5 " 4 - 10 " 5 - 19 calories per square centimetre.
50	Wright Air Dev. Centre Report WADC TR-58-642	Unclassified	Flash Blindness During Nuclear Operations. Metcalf and Horn. (Extracts Available as M.O.S. Document DGAW 157/59)
51	Wright Air Dev. Centre WADC TR-58-232 Oct. 1958	Unclassified	Visual Recovery Times from High-Intensity Flashes of Light. Metcalf and Horn.

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No.	Originator and Reference	Security Classification	Title
1	Army Operational Res. Group 11/56 (CD.9656)	Confidential	Visual Incapacity Following Exposure to a Nuclear Explosion: Flash Blindness, September, 1956.
2	Cttee on C.D. Sub-Cttee. On Sci. R & D. Panel B	Confidential	Thermal Radiation. Cutaneous Burns as a Function of Exposure Time.
3	Home Office CDJPS(EA)57/4 (CD.3146)	Confidential	Protective Measures Against Burning (especially Flash-burns) from the Atomic Bomb.
4	A.O.R.G. Report 21/49 (CD.2451)	Top Secret	Survey of Available Information (Feb.1950) on Flash-burning by the Thermal Radiation from an Atomic Bomb.
5	A.O.R.G. Memo 15 (CD.2954)	Top Secret	Memorandum on Flash Burning of Civilians by Atomic Bomb Attacks (April 1950)
6	B.J.S.M. (CD.7586)	Conf./U.K.Eyes	Thermal Radiation: Casualty Production. (6th January, 1955).
7	D.S.I.R./F.O.C. Joint Fire Res. Orgn. S.R. Note 6/51 (CD.3581)	Confidential	Thermal Radiation from an Atomic Explosion. The Protection Afforded by a Gas Mask.
8	A.O.R.G. Report 10/48	Unclassified	High Temperature Radiation and Pain on the Human Arm.
9	A .O.R.G. Report 10/50	Unclassified	Analysis of the Healing Times of Out-patient Scalds at the Birmingham Hospital.
10	A.O.R.G. Report 18/50	Unclassified	High Temperature Radiation and Pain: Location and Blackening of the Test Site.
11	M.R.C./R.N.P.R.C. RNP 44/113 SC.43	Confidential	Tests of Flash Burn Protective Cream.

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No.	Originator and Reference	Security Classification	Title
12	M.R.C./R.N.P.R.C. RNP 44/102 SC.37	Confidential	Protection from "Flash Burns" by Lightweight Fabrics.
13	Home Office CD(0)(SRTD)(PD)(55)	Unclassified	Thermal Radiation Characteristics of the Human Skin.
14	War Office MABCW(54)10 24/Gen/3598/AMD8	Secret	The Effect of Atomic Explosions on the Eyes.
15	Admiralty A.M.L. (Internal Report No. SB/95(M) October, 1955	Secret	Interim Note on Eye Protection from the Flash of Atomic Weapons.
16	R.A.E./I.A.M. F.P.R.C. Memo 69, 1955	Secret	Protection of the Eyes from Dazzle by an Atomic Explosion.
17	R.A.E./I.A.M. F.P.R.C. Paper 787, 1952	Unclassified	The Dazzle Effect of an Atomic Explosion at Night.
18	R.A.F./I.A.M. FPRC Report 304(a), June, 1941	-	The Effects of Flash from 304 Mk.12 Cannon Ammunition on Night Vision.
19	Dazzle Sub Group of Vision Cttee. FPRC Report 494, August, 1942	-	Progress Report
20	A.O.R.G. Report 8/56	Confidential	Part 1. Chorio-Retinal Burns.
21	A.O.R.G. Report 11/56	Confidential	Part 2. Flash Blindness
22	M.R.C. Report AWEC/P(57)104	Confidential	Flash Burns from Atomic Weapons. Butterfield and Drake-Seager.

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No.	Originator and Reference	Security Classification	Title
23	Reprint from "Surgery" December, 1956, Vol. 103 p. 655/665	Unclassified	Flash Burns from Atomic Weapons. Butterfield, et al.
24	Volume I (1942) and Volume VI (1954)	Unclassified	Text book of Ophthalmology. Duke - Elder.
25	Surgical Progress. Butterworth, London, 1951.	Unclassified	Pages 132-145. Burns, Flash, Butterfield, W.J.H.
26	A.W.R.E. Report T.11/58	Confidential	Operation Buffalo. Target Response Tests, Materials Group, Part 6. The Effects of Thermal Radiation from a Nuclear Explosion on Service Uniforms.
27	R.A.E. Technical Note ME.274.	Secret/Discreet	Visual Incapacitation of Aircrew by Nuclear Anti-Aircraft Weapons. Brinkworth.
28	Brit.J.Phys.Med., May, 1931	Unclassified	Penetration of Radiation into Animal Tissue. Pearson and Gair.
29	E.R. Drake-Seager, S.A.B./T.G.(58)2, Amended	Secret	Report on Visit to North America, 1956. Canadian Section.
30	AORG Report 18/58 Nov. 1958.	Confidential	The Tactical Implications of Flash Blindness and Chorioretinal Burns Caused by Nuclear Explosions. Part 1 Flash Blindness. E. G. Smith.
31	M.O.S., M.X.5 Report 8/55	Restricted	Experimental Methods of Flash Burning. (An Account of a Visit to Rochester University, New York). Blease

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No.	Originator and Reference	Security Classification	Title
32	War Office AORG Memo. K.7, May 1959	Restricted	Flash Blindness of Drivers. (Describes Trials to Study the Reactions of an M.T. Driver to Flash Blindness) Treadwell and Johnston
33	AORG Report 3/59 Feb. 1959	Confidential	The Tactical Implications of Flash Blindness and Chorioretinal Burns Caused by Nuclear Explosions. Part 2. Chorioretinal Burns. E. G. Smith.

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No.	Originator and Reference	Security Classification	Title
1	Medical Journal of Australia, 1944, Vol. 1, p.339	Unclassified	Burns on the Retina. Eccles and Flynn

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No.	Originator and Reference	Security Classification	Title
1	N.D.R.L. April, 1949 AD-95H (Home Office CD.5957)	Unclassified	An Estimate of the Relative Hazard of Beta and Gamma Radiation from Fission Products.
2	U.S.N./R.D.L. Report 394. (M.O.D. Ref. No. 111)	Confidential/ Discreet	Ratio of Lung Beta to Whole Body Dose during given Time Intervals after an Atomic Bomb Detonation.
3	U.S. Dept. of Commerce NBS. Handbook 59	Unclassified	Permissible Dose from External Sources of Ionising Radiation, 1954.
4	U.S.N./R.D.L. (DRB/54/15494)	Secret	Radiological Factors Affecting the Operation of Aircraft in Atomic Warfare. Prog. Report Pt.B., 1952.
5	1954 Tripartite Conf. U.S.A. Section No. 14	Secret/ U.K. Eyes	Biological Effects, Item 7 - Immediate Reactions to Radiation and Therapy Item 8 - Comparative Effects of Gamma and Neutrons, Item 9 - Delayed Effects in Man and Animals, Item 11 - Fallout in U.S.A., Item 12 - Agricultural Contamination, Item 14 - Personnel Decontamination (2 paras. only).
6	U.S. Nat. Bur. Stand Handbook 52 (DRB.54/ 7087)	Unclassified	Max. Permissible Amounts Radio Isotopes in Human Body and Max. Permissible Concentration in Air and Water.
7	U.S. At. En. Comm. AECD-3446 (DRB 54/ 4411)	Unclassified	Radiobiological Survey of Bikini Eniwetok and Likiop Atolls (testing specimens of fish plankton land plants, etc.).
8	U.S./A.E.C. Division of Biology and Medicine	Unclassified	Lecture at 7th Annual Industrial Health Conference, Houston, Texas, September, 1954.

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No.	Originator and Reference	Security Classification	Title
9	Rand Corpn. Memo. RM-1264 TIL P.60075	Military Use Only	Weight/feasibility calculation for Shielding of Truck Passengers. Harris.
10	CETG Report ITR. 1172 Teapot Project 37.3 TIL P.64139. (M.O.D. Ref. No. 208.)	Official Use Only	Evaluation of the Acute Inhalation Hazard from Radioactive Fallout Materials by Analysis of Results from Field Operations and Controlled Inhalation Studies in the Laboratory. Taplin, et al.
11	U.S. Naval Radiological Defence Laboratory Report USN/RDL.455 NS.081-001, 15.8.56. TIL P.66482	Military Use Only/Discreet	Residual Contamination of Plants, Animals, Coral and Water of the Marshall Isles Two Years following Operation Castle Fallout. Weiss, et al.
12	Wright, A.D.C. Report 57-118. TIL P.64800	Military Use Only	A radio-biology guide, April, 1957.
13	A.E.C. Press Release No. 969, 25.1.57.	Unclassified	Standards for protection against radiation. Code of Federal Regulations 10 CFR, Part 20. Effective from 28.2.57.
14	Radiation Research, Vol.4 No. 5, p.349, May, 1956	Unclassified	Nuclear Radiation at Hiroshima and Nagasaki. Article written April, 1951. Wilson (Cornell University).
15	Radiation Research, Vol.4 No.5, p.413, May, 1956	Unclassified	Effects of fast neutrons on mice. Carter, et al. (USNRDL).
16	U.S.A.E.C. Oak Ridge TID-5220. Part 2 TIL P.62524	Unclassified	Biological effects of external X - and Gamma Radiations. Zirkle. (This is Part 2 of Div. IV, Vol.22B, of the National Nuclear Energy Series, McGraw-Hill, 1954 - same title).

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No.	Originator and Reference	Security Classification	Title
17	Federal Civil Defence Admin. TB-11-1. Home Office CD.9806	Unclassified	Permissible Doses in the U.S.
18	Bulletin of Atomic Scientists, Vol. 11 No.9, November, 1955	Unclassified	Several articles on Genetic Aspects of Irradiation, including H.S. Mullens Contribution to Geneva Conference.
19	Air Force Special Weapons Centre, AFSWC-TN-56-2 TIL P.61674	Unclassified	Safe Levels of Contamination from Fission Products.
20	A.F.S.W.P. Report WT-746 (M.O.D. No. 23)	Confidential/ Atomic	Upshot/Knothole, Project 4.6. Beta-Gamma Skin Hazard in the Post Shot-Contaminated Area.
21	A.E.C. Oakridge Report WT-15 (deleted) (M.O.D. Ref. No.30)	Secret/Atomic	Operation Greenhouse, 1951. Scientific Director's Report, Annexe 2.3, Exposure Panels for the Biomedical Programme.
22	Naval Medical Research Institute, Armed Forces Institute of Pathology Report WT-22 (deleted) (M.O.D. Ref. No.31)	Secret/Atomic	Operation Greenhouse, 1951, Scientific Director's Report, Annexe 2.5. Mortality Rate as a Function of Nuclear and Thermal Radiation Dose. Mice, Swine, Dogs.
23	A.E.C. Oakridge. Extract of Report WT-89 (M.O.D. Ref. No. 34.)	Confidential	Atomic Radiological Safety. Organisation at Operation Greenhouse, 1951.

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No.	Originator and Reference	Security Classification	Title
24	A.E.C. Oakridge. University of Rochester's Report UR-301. (M.O.D. Ref. No.71.)		Personnel Protection in the Radioactive Inhalation Programme, 1955
25	A.E.C. Oakridge. Extract of Report WT-529, M.O.D. Ref. No. 36.	Secret/Atomic	Gamma Depth/Dose Measurement in Unit-Density Material (Lucite).
26	U.S.N.R.D.L. Report TR-27, 17th January, 1955. (M.O.D. Ref. No. 73.)	Unclassified	Adrenal Cortical Response in the Rat to X-Radiation in Terms of Corticosteronne Levels.
27	U.S.N.R.D.L. Report TR-29 19th January, 1955, (M.O.D. Ref. No. 74.)	Discreet (C.C.)	Recovery from Acute Radiation Injury in Mice following Administration of Rat Bone Marrow.
28	U.S.N.R.D.L. Report WT-794 (Cut), (M.O.D. Ref. No. 78)	Confidential/ Atomic	Operation Upshot/Knothole, Project 23.2. Bacteriological Studies of Animals exposed to Neutron Radiation, 1953.
29	U.S.N.R.D.L. Technical Memo. No.16. 22nd October, 1954. (M.O.D. Ref. No.100)	Discreet	On the Definition of Hazard in Radiological Assessments.
30	Naval Medical Research Institute and U.S.N.R.D.L. Report WT-923, October, 1954 (M.O.D. Ref. No.140)	Confidential/ Discreet	Operation Castle, Project 4.1, Final Report. Studies of Response of Human Beings Accidentally Exposed to Significant Fallout Radiation following Castle, Shot 1, 1st March, 1954.

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No.	Originator and Reference	Security Classification	Title
31	U.S.N.R.D.L. Report TR-47 2nd May, 1955. (M.O.D. Ref. No. 157.)	Confidential/ Discreet	Effectiveness Specifications for Radiological Defence Countermeasures. Defines Degree of Decontamination required in various Circumstances.
32	U.S.A.E.C. Paper HW-27620 16th February, 1953, (M.O.D. Ref. No. 171.)	Unclassified	The Uptake of Fission Fallout Material by Plants and Animals. U.S.A.E.C. Hanford, Atomic Products Operation, Biology Section Metabolism Unit Report entitled "The Absorption and Translocation by Plants of Radioactive Elements from 'Jangle' Soil".
33	A.E.C./O.R.N.L. Report AECU-2332, 4th April, 1952	Unclassified	External and Internal Exposure to Ionising Radiation and Maximum Permissible Concentration (M.P.C.) of Radioactive Contamination in Air and Water following an Atomic Explosion.
34	U.S.A.E.C. Greenhouse Programme 2 Report WT-2 (M.O.D. Ref. 268.)	Official Use Only	Operation Greenhouse, Scientific Director's Report, Annexe 2.1, Japtan Island. Development and Animal Production, Part I - Facilities, and Part II - Animal Colony. Fredric Flader Incorporated Report NEPA-624-FF-13, 31st January, 1948, (M.O.D. Ref. No. 283.)
35	University of California, Los Angeles School of Medicine, Report ITR-1177, August, 1955, (M.O.D. Ref. No. 283.)	Confidential/ Atomic	Operation Teapot, Project 37.1. Preliminary Report: The Factors influencing the Biological Fate and Persistence of Radioactive Fallout.
36	Army Chemical Centre, Chemical Warfare Laboratories Paper 11 Tri-C.88, August 1956. (M.O.D. Ref. No. 305.)	Confidential/ Discreet	Eleventh Tripartite Conference on Toxicological Warfare. U.S. Progress Report on Radiological Defence, 1st July, 1955 to 30th June, 1956.

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No.	Originator and Reference	Security Classification	Title
37	Oakridge National Laboratory Report ORNL-2304, 11th June, 1957, (M.O.D. Ref. No. 328.)	Unclassified	Health Safety. A Study of the Distribution and Examination of Uranium in Man - An Interim Report.
38	U.S.N.R.D.L./Commander, Task Group 7.3 Report WT-1012, 8th May, 1957, (M.O.D. Ref. No. 340).	Official Use Only	Operation Wigwam, Project 2.4. Final Report, superseding ITR-1012.
39	U.S.N.R.D.L. Report AD-145 (L) (Series D), 9th August, 1949, (M.O.D. Ref. No. 365.)	Unclassified	Training Industrial Personnel in Radiological Safety (Lecture, August, 1949).
40	Nucleonics, Vol. 10, p. 18 (1952).	Unclassified	Delayed Radiation Effects of Hiroshima and Nagasaki. Bugher.
41	An. Int. Med., Vol. 36, p. 279 (1952).	Unclassified	The Acute Radiation Syndrome. A Study of Nine Cases and a Review of the Problem. Hempelmann et al.
42	National Nuclear Energy Series, Division 8, Vol. 8, McGraw Hill Book Co., New York, 1956.	Unclassified	Medical Effects of the Atomic Bomb in Japan. Ed. Oughterson and Warren.
43	Science, Vol. 122, No. 3181, p. 1178 (1955).	Unclassified	Radioactive Fallout in the Marshall Islands.
44	J. Amer. Med. Assoc., Vol. 159, p. 430, 1955.	Unclassified	The Response of Human Beings Accidentally Exposed to Significant Fallout Radiation. Cronkite et al.

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No.	Originator and Reference	Security Classification	Title
45	U.S. Atomic Energy Commission Report TID-5358, 1956, (M.O.D. Ref. No. 269.)	Unclassified	Some Effects of Ionising Radiation on Human Beings Accidentally Exposed to Radiation and Fallout. Cronkite et al.
46	Science, Vol. 125, p. 219, 1957.	Unclassified	Strontium 90 in Man. Kulp et al.
47	Proc. Nat. Acad. Sci., Vol. 42, p. 365 and p. 945, 1956	Unclassified	Current Research Findings on Radioactive Fallout. Libby.
48	Science, Vol. 126, p. 485, 1957.	Unclassified	Strontium - Calcium Movement from Soil to Man. Comar et al.
49	U.S.N.R.D.L. Report TR-186 1957.	Unclassified	Radiological Hazard Evaluation. Alpen (Original presented at Twelfth Tripartite Conference on Toxicological Warfare, 1957).
50	U.S. Code of Federal Regulations No. 10 (10CFR), Part 20.	Unclassified	Standards of Protection against Radiation.
51	A.E.C., Oakridge Report WT-6 (M.O.D. Ref. No. 180).	Secret/Atomic	Operation Greenhouse, Scientific Director's Report of Atomic Weapon Tests - Radiobiological and Flash Burn Data, Part VII - Swine, Part VIII - Dogs, and Part IX - Thermal Burns.
52	A.F.S.W.P. Report ITR-1464	Official Use Only	Operation Plumbbob, Project 32.3, Evaluation of Counter Measures System, Components and Operational Procedures.
53	Advanced Technology Corporation, 15th November, 1953, T.I.L. Ref. P. 73929		Radiochemical Laboratory Handbook (A 379 Page Laboratory Manual of Techniques).

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No.	Originator and Reference	Security Classification	Title
54	Nucleonics, Vol. 17, No. 4, pp. 106 and 107		Reports of Criticality Accidents and Resulting Radiation Sickness:- (a) Yugoslavia, 15th October, 1958. (b) Los Alamos, 30th December, 1958.
55	Bulletin of Atomic Scientists, Vol. 14, No. 1, January, 1958.	Unclassified	Special Issue dealing with Radiation and Man.
56	U.S.N.R.D.L. Report TR-77, T.I.L. Ref. No. P. 71298.	Unclassified	Uptake, Distribution and Retention of Fission Products in Tissues of Mice exposed to a Simulant of Fallout from a Nuclear Detonation. I. Simulant of Fallout from a Detonation under Seawater.
57	A.E.C. Press Release No. 660, 11th July, 1955.	Unclassified	Draft Regulations on Standards for Protection against Radiation. (Includes Definitions).
58	A.F.S.W.C. Kirtland A.F.B. Report, A.F.S.W.C-TN-57-30		Limits for Radiation. Control and Release of Air Force Material contaminated with Fission Products.
59	U.S.A.F. School of Aviation Medicine, Randolph Field. TIL No. P. 66579.	Unclassified	Clinical and Histological Observations of Radiation Damage occurring in the Mammalian Eye. Cibis et al. (April, 1955)
60	Nature, Vol. 181, No. 4626, p. 1792-3, 28th June, 1958.	Unclassified	Letter. Removal of Internally Deposited Plutonium. Smith, V.H., Hanford Laboratories.
61	U.S.N/R.D.L. Report TR-256 Aug. 1958.	Unclassified	Protecting and Cleaning Hands Contaminated by Synthetic Fallout Under Field Conditions.

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No.	Originator and Reference	Security Classification	Title
62	A/Conf. 15/P/1008 June 1958	Confidential	2nd U.N. Conference. Radio-strontium Metabolism and Decontamination in Man; Chelation in Biology and Medicine. Laszlo and Spenser.
63	LA-2224 May 1958	Unclassified	Rate of Recovery from Radiation Damage and its Possible Relationship to Life Shortening in Mice. Storer.
64	HW-51754 Sept. 1957	Unclassified	Detection of Plutonium Contamination in Humans by the Autoradiographic Method. Dockum, et al.
65	TID-7551 June 1957	Unclassified	5th Atomic Energy Commission Air Cleaning Conference Held at the Harvard Air Cleaning Laboratory.
66	SO-6200 Sept. 1957	Unclassified	Hazards and Safety Measure for Nuclear Powered Merchant Ships - An Annotated Bibliography. A. D. Little Inc.
67	USN/RDL Report TR-182 Aug. 1957	Unclassified	A Study of Maximum Permissible Concentration of Radioactive Fallout in Water and Air Based Upon Military Exposure Criteria. Teresi and Newcombe.
68	UWFL-47 March 1957	Unclassified	Survey of Radioactivity in the Sea and in Pelagic Marine Life Waste of the Marshal Islands, Sept. 1-20 1956. Seymour, et al.
69	ANL-5808 Jan. 1958	Unclassified	Environmental Radioactivity at Argonne National Laboratory. Sedlet.
70	HW-52287 Oct. 1957	Unclassified	Calculation of Maximum Permissible Concentration in Air for Ru. 106 Particles. Bair.

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No.	Originator and Reference	Security Classification	Title
71	A/Conf. 15/P/888	Confidential	2nd U.N. Conference. Hematologic Effects in Man of Low Level Radiation Exposure. Dobson and Chupp.
72	11th Tri. Conf. on Tox. Warfare U.S. Paper 11-TRI-294	Unclassified	Data Pertaining to Shortening of Life Span by Ionizing Radiation.
73	Tech. Command Interim Report No. 627 Proj. 4-12-07-001 Feb. 1951	Confidential	The Proper Role of Detergents in Relation to Radiological Decontamination. Levin.
74	11th Tri. Conf. on Tox. Warfare U.S. Paper 11-TRI-C115	Confidential	Medium Lethal Dose for a Man Exposed in a Radioactive Fallout Field.
75	11th Tri. Conf. on Tox. Warfare U.S. Paper 11-TRI-273	Unclassified	Evaluation of the External Human Hazard due to Radioactive Fallout.
76	USAEC Report WASH-1008	Unclassified	Biological Hazard to Man of Carbon 14 from Nuclear Weapons. J. R. Totter et al.
77	Stanford Research Institute Nov. 1958	Unclassified	Systems Analysis of Radiological Defence
78	11-Tri-S-479 (US Army Chem. Corps)	Secret	11th Trip. Conf. on Tox. Warfare 1956. Final Report.

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No.	Originator and Reference	Security Classification	Title
79	Johns Hopkins University, Operation Res. Office Report ORO-T-357 July 1956	Unclassified	Biological Effects of Whole Body Gamma Radiation on Human Beings. H.O. Davidson

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No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T11/57	Official Use Only	Operation Buffalo: The Dose Received at Various Parts of the Body by a Man Walking over Contaminated Ground.
2	Air Ministry Sc. 2 Memo. 254	Top Secret Atomic U.K.E.O.	The Danger to Bombers from Radio-active Clouds over a Realistic Target Area.
3	Atomic Scientists Journal Vol. 4, No. 2, Nov. 1954	Unclassified	Bikini Ash
4	Home Office (CD.7241)	Confidential U.K. Eyes Only	The Initial Gamma Radiation Hazard from Very Large Weapons.
5	M of Supply, A.E.R.E. (Feb. 1952) HP/M31	Confidential	Estimation of Energy Tolerances for Fission Products in Air and Water.
6	M of Supply, A.E.R.E. HP/M23	Confidential	Energy Tolerance for Fission Products in Drinking Water.
7	The Listener 28th October, 1954	Unclassified	The Dangers of Radioactive Dust.
8	A.R. Laboratory (Jan. 1950) Report N1/R. 322	Secret/Discreet	Effect of Continued Exposure to Radiation from Decaying Fission Products.
9	A.E.R.E./H.O. HP/R/737 (CD/SA/23)	Unclassified	The Hazard from Inhaled Fission Products in Rescue Operations.
10	M of Supply A.R.E. (1948) A.R.E. Report 1/48	Secret	Part 3. Gamma Deaths from an Open Window.

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No.	Originator and Reference	Security Classification	Title
11	Medical Research Council P.A.B.E. Report No. 11	Secret	Hazards of Radioactive Dust.
12	A.W.R.E. 0-23/54	Secret	Decontamination of Clothing II. Laundry Investigations and Recommendations.
13	A.W.R.E. 0-22/54	Secret	Decontamination of Clothing I. Laboratory Investigations.
14	"Nucleonics" 12/1954 No. 9, 39.	Unclassified	Evaluating Reactor Hazards from Airborne Fission Products.
15	A.E.R.E. HP/R.1495	Unclassified	Derivation of Maximum Permissible Levels of Contamination of Surfaces by Radioactive Materials.
16	A.E.R.E. Report EL-R.1798	Secret	10th Tripartite Conference on Toxicological Warfare. A Report on the Meetings on Radiological Defence. Taylor.
17	British Journal of Radiology. Supplement No.6, 1955.	Unclassified	Recommendations of the International Commission on Radiological Protection, 1955.
18	Home Office	Restricted	Report of a Home Office Committee on the Ventilation of Protected Accommodation under Fallout Conditions.
19	Brit. J. Indus. Med. Vol.9, No.2, April, 1952	Unclassified	Dust Sampling and Lung Diseases. Davies.
20	Agricultural Res. Cttee. AERE Report ARC/RBC.5	Official Use Only	Ingestion of Fallout by Grazing Animals. Scott Russel, et al.

U.K. Reports PERSONNEL, ANIMALS AND VEGETATION: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
21	"Nature", Vol. 177 No. 4513, p.787, 28.4.56.	Unclassified	Genetic Effect of X-rays in relation to Dose Rate in Drosophila. Clark.
22	R.A.E. Library, Bibliography No. 195	Unclassified	List of (Unclassified) References on Atomic, Photon and Ion Propulsion of Aircraft; the Shielding of Aircraft nuclear reactors; the Medical Hazards of Atomic Powered Aircraft; and the Effect of Atomic Radiation on Aircraft Materials and Components.
23	A.W.R.E. Report O.34/56	Official Use Only	The Ingestion of Food contaminated by Atomic Explosions.
24	A.W.R.E. Report T.65/57	Confidential	Operation Buffalo. Biology Group, Part IV(b), The Effects of Neutron and Gamma Irradiation upon Foodstuffs.
25	Medical Research Council H.M.S.O. Cmd. 9780, June, 1956.	Unclassified	The Hazards to Man of Nuclear and Allied Radiations.
26	A.W.R.E. Report T4/57	Confidential	Decontamination of Radioactively Contaminated Drinking Water in the Field.
27	R.A.E. Tech. Memo. ARM/1728	Secret	Incapacitation of Aircrew by Irradiation.
28	Ministry of Supply, D.A.W. Plans Memo. XY/144/03	Secret	Capabilities of Aircrew after Irrediation by Counter-Weapons (Equipment Considerations).
29	A.W.R.E. Report H12/52	Official Use Only	The Penetration of Gamma Radiation through the Walls of a Slit Trench.
30	M.R.C./A.E.R.E. 1955		The Effects of Gamma on Animals. Loutit.

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No.	Originator and Reference	Security Classification	Title
31	Nature, Vol. 182, No. 4648, pp. 1473-1478, 29th November, 1958.	Unclassified	Radioactivity due to Fission Products in Biological Material. Article by Mayneord et al.
32	A.E.R.E. Paper HP/R 1677	Official Use Only	European Atomic Energy Society Symposium of Nuclear Reactors, 23rd-24th March, 1955. Chamberlain.
33	Nature, Vol. 182, No. 4652, pp. 1787 1790	Unclassified	A. Radiobiochemical Lesion in Animal Cells (Survey Article by Ord and Stocken).
			B. Magnitude of Radiation Effect on the Process of Synthesis of Deoxyribonucleic Acid. Lajtha et al.
34	A.E.R.E. Report AERE EL/R 1798, 1955. (M.O.D. Ref. No. 180)	Secret	Tenth Tripartite Conference on Toxicological Warfare (1955).
35	A.E.R.E. Paper AERE EL/R 2118, (M.O.D. Ref. No. 281)	Secret	Eleventh Tripartite Conference on Toxicological Warfare. Report on the Meetings on Radiological Defence, 1956. (Includes also Thermal Burn and Flash Blindness Data).
36	A.W.R.E. Report TCR 25/57 September, 1957. (M.O.D. No. 390)	Secret U.K. Eyes Only	Twelfth Tripartite Conference on Toxicological Warfare. a Report on the Meetings on Radiological Defence.
37	A.W.R.E. Report T54/57.	Confidential	The Hazards to Air Crew Flying through an Atomic Cloud.
38	Tripartite Conf. Nov. 1955 Paper TC6/55	Unclassified	Radiation Sickness in Man and Monkey. Loutit.

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No.	Originator and Reference	Security Classification	Title
39	C.D.E.E. Porton Tech. Paper (R) 16 Nov. 1958.	Confidential	Radiological Decontamination: Removal of Dry Fallout from Skin and Clothing. E. Neale and Elizabeth H. Letts.
40	13th Tripartite Tox. Conf. Sept. 1958. Admiralty Paper DPR/BWS/144/58	Confidential	Contamination by Radioactive Fission Products. Acceptable Levels of Personal Contamination under Exceptional Circumstances. B. W. Soole.
41	ARL/N4/0775 Dec. 1958	Unclassified	Manufacturing Specification for ARL Radiological Barrier Cream Type P.2. E. W. Jackson.
42	Nature Vol. 182 pp. 1118-9 (Oct. 25th 1958)	Unclassified	Summary of Second U.N. Geneva Conference Proceedings Relating to the Biological Effects of Radiation. J. F. Loutit.
43	H.Pan/S.23 Dec. 1957.	Official Use Only	Treatment of Personal Radioactivity Contamination. An Outline of the Practice in the U.K.A.E.A. J. B. Lynch.
44	Atomic Energy Research Estab. Report AERE-L.101 (2nd Edition of AERE Report HP/L23) March, 1959.	Unclassified	A Short Course in Radiological Protection Editor R. J. Sherwood
45	War Office Paper 70/Nuclear/61, (GS(W).11) March, 1959. Also ARL/R 867.14.	Confidential	The Beta Dose to the Infantryman's Head. Maj. W. T. M. Gaskell.

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No.	Originator and Reference	Security Classification	Title
46	A/Conf. 15/P/2324	Confidential	2nd U.N. Conference. Observation on Recovery and Irreversible Radiation Injury in Mammals. Hursh. et al.
47	Nature Vol. 180 p. 1466 (Dec. 28th 1957)	Unclassified	The General Radiation Syndrome: Initial Reaction in the Monkey. (Letter by C. G. Hunter et al)
48	13th Tripartite Tox. Conf. September, 1958 U.K. Paper	Confidential	Acceptable Levels of Water Contamination.
49	13th Tripartite Tox. Conf. Sept. 1958 U.K. Paper	Confidential	Contamination of Body Surfaces and Personal Equipment by Radioactive Material.
50	13th Tripartite Tox. Conf. Sept. 1958. Admiralty Paper DPR/BWS/143/58	Confidential	A Comparison of the Internal and External Radiation Hazards to a Man Exposed to a Cloud of Fission Products from a Nuclear Explosion. B. W. Soole.
51	13th Trip. Conf. on Tox. Warfare Paper TCR7/58	Confidential	The relative Importance of External and Inhalation Hazards to Personnel in Fallout Areas and in Aircraft. J. K. Jones.
52	13th Trip, Conf. on Tox. Warfare Paper TCR2/58.	Confidential	Suggested Wartime Doses of Ionizing Radiation for Home Defence Purposes. Stanbury.
53	Tripartite Conf. Nov. 1955 Paper TC7/55	Unclassified	Contamination of Wounds with Fallout from Nuclear Weapons. Barnes and Loutit.

U.K. Reports PERSONNEL, ANIMALS AND VEGETATION: Nuclear Radiation, Contamiration and Decontamination

No.	Originator and Reference	Security Classification	Title
54	Medical Research Council Report PABE/100 Feb. 1957.	Official Use Only	Review of Maximum Permissible Levels of Fallout Contamination for Food and Drinking Water G. J. Neary.
55	T.C.R. 9/58 Feb. 1959	Secret U.K. Eyes Only	13th Tripartite Conference on Toxicological Warfare. A Report of the Meetings on Radiological Defence. Barnes, Stanbury and Abson
56	Res. & Dev. Branch U.K.A.E.A. Risley RGL-IB/R21 1957.	Unclassified	Information Bibliography. General Health Physics.
57	12th Tri. Conf. on Tox. Warfare Paper TCR20/57	Confidential	Decontamination of Personnel and Equipment - Techniques and Equipment Catherall and Stevenson
58	12th Tri. Conf. on Tox. Warfare U.K. Paper	Restricted	The Operational Aspects of Radiological Decontamination of Personnel. D. B. Janisch
59	ARL/R1/C775 July 1957	Unclassified	Decontamination Experiments on Human and Animal Skin. E. W. Jackson
60	ARL/N2/C763	Unclassified	Techniques for the Decontamination of Ships and Personnel. Jackson.
61	A.E.R.E. Report EL/R2118	Secret	11th Tripartite Conference on Toxicological Warfare - A Report of the Meetings on Radiological Defence Barnes and Taylor.

U.K. Reports PERSONNEL, ANIMALS AND VEGETATION: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
62	ARL/N2/C775 June 1956	Unclassified	Decontamination of Personnel - Use of Hand Held Spray
63	Home Office Report CD/SA61 May, 1955	Secret	Neptunium as a Residual Radiation Hazard
64	AERE Report HP/R551 Aug. 1950	Unclassified	Estimation of Maximum Permissible Levels of Radiation
65	AERE Report HP/R731 Jan. 1951	Confidential	The Problem of Airborne Radioactive Dust in Atomic Energy Work. Proceedings of a Symposium Held at A.E.R.E. January 17th, 1951.
66	AERE Report HP/M101 March, 1956	Official Use Only	The Transportation of Radioactive Materials.
67	DSIR Water Pollution Res. Lab. Report No. 8 Nov. 1955	Secret	The Removal of Radioactive Iodine from Water by Passage through Silvered Kieselzuhr
68	ARL/N1/C775 Nov. 1955	Confidential	Evaluation of an Experimental Personnel Cleansing Booth. Jackson
69	A.W.R.E. Report T57/58	Unclassified	Operation Buffalo. Biology Group. Part 5. The Entry of Fission Products Into Food Chains.

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PERSONNEL, ANIMALS AND VEGETATION: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
70	AERE Report HP/R2730 Nov. 1958	Unclassified	Radio Strontium in Soil, Herbage, Animal Bone and Milk Samples from the U.K. 1957 Results. F. J. Bryant et al.
71	M.O.S. C.D.E.E. Porton Note. No. 70 Jan. 1959	Secret	Contact Hazards: The Pick-up of Contaminant on Crawling Over a Contaminated Grass Area.
72	Home Office Report CD/SA.71	Confidential	Numbers of Casualties from a Ground Burst Megaton Weapon Likely to be Personally Contaminated by Radioactive Material. E. C. Allen
73	AERE Report HP/M108	Official Use Only	Radio-Strontium Fallout in Soil, Plant and Bone up to December, 1955.

Miscellaneous Reports PERSONNEL, ANIMALS, AND VEGETATION: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	Japanese Society for the Promotion of Science, 1956 A.W.R.E. Library Reference 16927.	Unclassified	Research on the Effects and Influences of the Nuclear Bomb Test Explosions, Vols. 1 and 2.
2	United Nations General Assembly Office Records Thirteenth Session, Supplement No. 17 (A/3838).	Unclassified	Report of the United Nations Scientific Committee on the Effects of Atomic Radiations.
3	Philips Technical Review, Vol. 19, No. 9, p. 264, 1957/58.	Unclassified	Dosimetry of the Very Weak X-Radiation Generated in Television Receivers and X-Ray Defraction Apparatus. Oosterkamp et al. (Gives Dose Rates from Certain Types of Receiver).
4	A.E.C.L., Chalk River. Report No. 647, T.I.L. Ref. P.71784, June, 1958.	Unclassified	Population Risks from Nuclear Radiation. Newcombe (Estimates Relative Hazards from Nuclear Testing, War, Automobile Deaths, and Industrial Accidents).
5	Canadian Defence Research Board, Panel on Radiation Protection and Treatment.		Ninth Meeting, 23rd July, 1957 (T.I.L. Ref. P.70857). Tenth Meeting, 29th-30th November, 1957 (T.I.L. Ref. P.70518). Eleventh Meeting, 3rd May, 1958 (T.I.L. Ref. P.72464).
6	A.E.C.L. Report 629, 1958 T.I.L. Ref. P.72566.	Unclassified	Canadian Experience in the Measurement and Control of Radiation Hazards in Uranium, Mines and Mills (mainly concerned with Radon Concentration in Mines.
7	A.E.C.L. Report No. 594, T.I.L. Ref. P.72555.	Unclassified	Health and Safety in Canadian Operations.

U.K. Reports DAMAGE TO MATERIALS: Blast

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. Report T18/57	Confidential	Operation Buffalo: Target Response, Biology Group.

U.S. Reports. DAMAGE TO MATERIALS: BLAST

No.	Originator and Reference	Security Classification	Title
1	Ballistics Research Laboratory Memo. No. 626	Unclassified	Tests on Glazing Materials.
2	A.F.S.W.P. Report WT-1461	Official Use only	Operation Plumbbob. Project 38.1. Blast Effects on Glass Vacuum Containers.

U.K. Reports DAMAGE TO MATERIALS: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. Report T32/57	Confidential	Operation Buffalo: Interim Report, Target Response, Materials Group.
2	A.W.R.E. Report T77/54	Confidential	Effects on Respirators, Anti-gas.
3	A.W.R.E. Report T5/57	Confidential	Operation Buffalo: Interim Report, Target Response, Explosive Group.
4	M.O.S.S./AT/3 9 June 1957.	Confidential/ Atomic	Effects of Atomic Explosions on Conventional Explosives, Propellants and Initiators. Record of Discussion at O.C.O. on 19th November, 1956. Lewis E.G.
5	A.R.D.E. Memo (B) 1/58	Confidential	The Effects of Atomic Weapons on Ammunition. 1. Unguided Rockets, Litton J.C.
6	E.R.D.E. Report 9/R/58	Confidential/ Discreet	Operation Buffalo: The Effects on Propellants of Exposure to an Atomic Weapon Explosion. Cole L.D.
7	A.W.R.E. Report T5/58	Confidential	Operation Buffalo: Materials Group. Part 8A. Effects of a Nuclear Explosion on Petrol Pipe-Lines.
8	A.W.R.E. Report T7/58	Confidential	Operation Buffalo: Explosives Group, Final Report Part 1. Introduction.
9	A.W.R.E. Report T10/58	Confidential	Operation Buffalo. Materials Group, Part 8B. The Effect of a Nuclear Explosion on Jerrican Stacks.
10	A.W.R.E. Report T17/58	Confidential	Operation Buffalo: Target Response Tests, Materials Group. Part 1 - General Introduction.
11	A.W.R.E. Report T64/57	Confidential	Operation Buffalo. Effects of an Atomic Explosion on Medical Supplies.

U.S. Reports. DAMAGE TO MATERIALS: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	A.F.S.W.P. Report WT-1216 (M.O.D. Ref. No. 332)	Unclassified	Operation Teapot: Project 32.3. The Effect of Nuclear Explosions on Meat and Meat Products.
2	A.F.S.W.P. Report WT-1215 (M.O.D. Ref. No. 333)	Unclassified	Operation Teapot: Project 32.5. Effects of Nuclear Explosions on Frozen Foods (1955).
3	A.F.S.W.P. Report WT-1214 (M.O.D. Ref. No. 334)	Unclassified	Operation Teapot: Project 32.4. The Effect of Nuclear Explosions on Semi-perishable Foods and Food Packaging (1955).
4	A.F.S.W.P. Report WT-1213 (M.O.D. Ref. No. 335)	Unclassified	Operation Teapot: Project 32.2(a). The Effect of Nuclear Explosions on Commercial Packaged Beverages (1955)
5	A.F.S.W.P. Report WT-1163 (M.O.D. Ref. No. 336)	Unclassified	Operation Teapot: Project 32.1. Effects of Nuclear Explosions on Bulk Food Staples (1955).
6	A.F.S.W.P. Report WT-1212	Official Use only	Operation Teapot: Project 32.2. Effects of Nuclear Explosions on Canned Foods.
7	A.F.S.W.P. Report WT-1222	Official Use only	Operation Teapot: Project 32. Exposure of Foods and Food Stuffs to Nuclear Explosions (A Summary of Results).

U.K. Reports EFFECTS ON ELECTRONIC SYSTEMS AND EQUIPMENT: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
1	1957 Tripartite Conf. W.O. Paper AWEC/p(57)113	Confidential	Transient Heat Effects on Whip Type Aerials. Lt.Col. Brenchley.

U.S. Reports EFFECTS ON ELECTRONIC SYSTEMS AND EQUIPMENT: Nuclear Radiation, Contamination and Decontamination.

No.	Originator and Reference	Security Classification	Title
1	Fredric Flader Inc. Eng. Physics Division Report NEPA.624-FF-13 CD.10074 (M.O.D. Ref. 282)	Unclassified	Effects of Fission Produced Radiation on Electronic Equipment. 1948. (Results of tests with Argonne pile, up to 100 hours at 10^{11} neutrons and 10^{10} gamma rays per sq. c.m. per sec.)
2	Proc. I.R.E. Vol.45 No.7 p.931, July,1957.	Unclassified	The Effect of Nuclear Radiation on Selected Semi-conductor Devices. Keister and Stewart.
3	"Nucleonics", Vol. 14 No. 9, p.66, September, 1956.	Unclassified	Damaging Effects of Radiation on Electronic Components.
4	University of California Los Angeles, Report WT-803 (Cut). (M.O.D. Ref. 79)	Confidential/ Atomic	Measurement of Fast Neutrons by Effects on Semi-conductors.
5	Civil Effects Test Group Report ITR-1170,May 1955 (M.O.D. Ref. 246)	Confidential/ Atomic	Operation Teapot. Project 39.5. Preliminary Report. Measurement and Permanent Recording of Fast Neutrons by Effects on Semi-conductors (P type Germanium) P and N type Gold/Germaniun, with and without Cadmium shielding.
6	Phil Mag.Vol.45, Page 651, 1954.	Unclassified	The Pile Irradiation of Quartz Crystal Oscillators. Johnson and Pease.
7	Proc.I.E.E.Vol.104C, Page 174, 1956.	Unclassified	Properties of Synthetic Quartz Oscillator Crystals. Brown and Thomas.
8	American Mineralogist, Vol.31, Page 58, 1946.	Unclassified	The Effect of Radiation on the Elasticity of Quartz. Froudel.

U.S. Reports EFFECTS ON ELECTRONIC SYSTEMS AND EQUIPMENT: Nuclear Radiation, Contamination and Decontamination.

No.	Originator and Reference	Security Classification	Title
9	S.C.E.L. Fort Monmouth, 1957	-	Proceedings of the 11th Annual Symposium on Frequency Control. (Various papers)
10	"Nucleonics", Vol.16, No.3, March 1958. Page 122.	Unclassified	Radiation Effects on Quartz Crystals, especially on Frequency of Oscillation. (Includes Bibliography).
11	Diamond Ordnance Fuze Labs. Tech.Report TR-452. 10th April, 1957	Unclassified	The Effects of Short Duration Neutron Radiation on Semi-conductor Devices. Behrens and Shaull.
12	"Nucleonics" Vol.16, No.6, June, 1958. Pages 73-77.	Unclassified	Electronic Equipment: Radiation Effects in Magnetic Materials. Gordon et al.
13	Admiral Corpn. 1957	Unclassified	The Effects of Nuclear Radiation on Electronic Components. (There are several of these reports dealing with the detailed results of an extensive investigation of the effects of Pile Irradiation on Resistors, Condensers, Valves, Insulating Materials, etc.).

CONFIDENTIAL/DISCREET

U.K. Reports EFFECTS ON ELECTRONIC SYSTEMS AND EQUIPMENT: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	P.O. Research Station (CD.9587)	Confidential	The Effect of Heavy Dosages of Gamma Radiation on Electronic Equipment, May, 1956.
2	R.A.E. Library Bibliography No. 195	Unclassified	List of (Unclassified) References on Atomic, Photon, and Ion Propulsion of Aircraft; the Shielding of Aircraft Nuclear Reactors; the Medical Hazards of Atomic Powered Aircraft; and the Effect of Atomic Radiation on Aircraft Materials and Components.
3	"Nature", Vol. 179 No. 4565, p.864, 27th April, 1957	Unclassified	Effects of Nuclear Radiation on Semi-conductors (Letter). Gorton.
4	A.W.R.E. Report T50/58, February, 1959	Official Use Only	Operation Antler, Target Response Group. The Recording Techniques used in the study of the Electro-magnetic effects on Ground Radar Equipment. McLeod.

CONFIDENTIAL/DISCREET

No.	Originator and Reference	Security Classification	Title
1	U.S. N.Y. Naval Shipyard Mat.Lab.Proj. 5046.3 Part 56 Final Report N.S. 081-001	Unclassified	Critical Thermal Energies of Plastic Radome Materials.

Miscellaneous Reports. EFFECTS ON ELECTRONIC SYSTEMS AND EQUIPMENT: Combined Effects on Equipment and Propagation.

No.	Originator and Reference	Security Classification	Title
1	Radio Teknika Volume 10 No.11 Page 80 (1955)	Unclassified	Radar Reflections from Lightening. B.ARANUL'KO FEDOTOV. In Russian, for English precis see Science Abstracts B, No.3171 August 1956.

U.K. Reports   EFFECTS ON ELECTRONIC SYSTEMS AND EQUIPMENT: Combined Effects on Equipment and Propagation.

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T7/57	Confidential	Operation Buffalo: Target Response, Electronics Group.
2	A.W.R.E. T16/57	Confidential	Operation Buffalo: Target Response Tests: Effects on Communications' Cables. Lt. Col. Brenchley.
3	1957 Tripartite Conf. Paper AWEC/P(57)19.	Confidential	Communication Cables at Operation Buffalo. 1956.
4	1957 Tripartite Conf. A.M. Paper AWEC/P(57)44.	Secret/Atomic	The Vulnerability of Radar to Nuclear Explosions. Henderson.
5	DRP(AES)(TR)/P(58)2. 22nd January 1958.	Secret/Atomic	Radar Responses from Bursts at Operation Antler. Proof preliminary data.
6	A.W.R.E. Report T15/57	Confidential	Operation Buffalo. Electronics Group. Effects on Field Wireless Tranceivers, Aerials and Batteries.
7	A.W.R.E. Report T14/57	Confidential	Operation Buffalo. Electronics Group. Effects on Radar Type 14, Generating Sets and Test Equipment.
8	R.R.E. Memo. No. 1561 September, 1958	Secret U.K. Eyes Only	The Radar Response from an Atomic Explosion. S.S.D. Jones.

U.S. Reports EFFECTS ON ELECTRONIC SYSTEMS AND EQUIPMENT: Combined Effects on Equipment and Propagation.

No.	Originator and Reference	Security Classification	Title
1	U.S.AFM 200-20 (M.O.D. Ref. No. 407/053/03/35)	Confidential/ Atomic	Radar Target Intelligence.
2	A.F.S.W.P. Report WT-761 (M.O.D. Ref. 214)	Secret	Operation Upshot Knothole. March-June, 1953. Effectiveness of Fast Scan Radar for Fire-ball Studies and Weapons Tracking; Project 6.13, June, 1955.
3	Wright Air Development Centre, Tech.Report 55/159. (M.O.D. Ref. 249)	Secret	Aircraft Instrumentation for Special Weapons Effects Tests.
4	1957 Tripartite Conf. Paper No. 23.	Secret/Atomic	Effect of Nuclear Explosions on Propagation of Electromagnetic Waves. Shuler.
5	U.S.N.R.L. Paper 00761/RD (M.O.D. Ref. No. 326)	Secret/Atomic	The Effects of Nuclear Explosions on the Propagation of Electro-Magnetic Waves. Shuler. (Paper for 1957 Tripartite Conference).
6	U.S. Army Ordnance Conf. June 1957. Volume 3.	Confidential/ Discreet	A. The Ionospheric Effects of Nuclear Explosions. Daniels and Harris. B. Radar Observations of Atomic Clouds. Swingle.
7	A.F.S.W.P. (Availability in U.K. unknown)	(Secret/ Discreet)	Operation Plumbbob, Project 6.2. Near Field Measurements of the Electro-Magnetic Effect. Report by Diamond Ordnance Fuse Labs. Project 6.5. Effects of Nuclear Radiation on NIKE. B.G.M. Components, Materials and Systems. Report by White Sands Proving Ground.
8	A.F.S.W.P. (Availability in U.K. Unknown)	(Secret/ Discreet)	Operation Hardtack. Radiation Effects on Electronic Fuse Components. Report by Diamond Ordnance Fuse Labs. (Covers Nuclear and Electro-magnetic effects on Active Missile Fuse Systems before, during and after Nuclear Detonations.)

U.K. Reports

DAMAGE TO AIRCRAFT: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	Air Ministry Sc. 2 Memo. 254	Top Secret Atomic U.K.E.O.	The Danger to Bombers from Radio-Active Clouds over a Realistic Target Area.
2	A.W.R.E. T106/54	Secret	The Prevention and Removal of Radioactive Contamination, Part VI. Decontamination of Aircraft, and Health Control at Woomera and Amberley.
3	Admiralty TIB(BR)50	Secret	A Report on the Radiological Decontamination of Aircraft.
4	Royal Aircraft Est. Library Bibliography No. 195.	Unclassified	List of (unclassified) References on Atomic, Photon, and Ion Propulsion of Aircraft; the Shielding of Aircraft Nuclear Reactors; the Medical Hazards of Atomic Powered Aircraft; and the Effect of Atomic Radiation on Aircraft Materials and Components.
5	A.W.R.E. Report No. T63/57.	Official Use Only	The Handling, Servicing, and Decontamination of Radioactive Aircraft.
6	A.W.R.E. Report No. T33/57	Confidential	Operation Mosaic. Aircraft Decontamination.
7	Ministry of Supply, D.A.W.(Plans)Memo XY/98/05	Secret	Protection in Military Aircraft against the Products of Nuclear Fission.
8	Ministry of Supply, D.A.W.(Plans)Memo. XY/144/03.	Secret	Capability of Air Crew after Irradiation by Counter-weapons. (Equipment Considerations)
9	AP(N)123 1957	Restricted	Draft Handbook on the Radiological Decontamination of Aircraft.
10	Air Ministry Science 2. Memo 230 (1954)	Secret/ Atomic	The Danger to Bombers from Radioactive Clouds Over a Simplified Target Area.

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DAMAGE TO AIRCRAFT: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	Air Ministry Sc. 2 Memo. 254	Top Secret Atomic U.K.E.O.	The Danger to Bombers from Radio-Active Clouds over a Realistic Target Area.
2	A.W.R.E. T106/54	Secret	The Prevention and Removal of Radioactive Contamination, Part VI. Decontamination of Aircraft, and Health Control at Woomera and Amberley.
3	Admiralty TIB(BR)50	Secret	A Report on the Radiological Decontamination of Aircraft.
4	Royal Aircraft Est. Library Bibliography No. 195.	Unclassified	List of (unclassified) References on Atomic, Photon, and Ion Propulsion of Aircraft; the Shielding of Aircraft Nuclear Reactors; the Medical Hazards of Atomic Powered Aircraft; and the Effect of Atomic Radiation on Aircraft Materials and Components.
5	A.W.R.E. Report No. T63/57.	Official Use Only	The Handling, Servicing, and Decontamination of Radioactive Aircraft.
6	A.W.R.E. Report No. T33/57	Confidential	Operation Mosaic. Aircraft Decontamination.
7	Ministry of Supply, D.A.W.(Plans)Memo XY/98/05	Secret	Protection in Military Aircraft against the Products of Nuclear Fission.
8	Ministry of Supply, D.A.W.(Plans)Memo. XY/144/03.	Secret	Capability of Air Crew after Irradiation by Counter-weapons. (Equipment Considerations)
9	AP(N)123 1957	Restricted	Draft Handbook on the Radiological Decontamination of Aircraft.
10	Air Ministry Science 2. Memo 230 (1954)	Secret/ Atomic	The Danger to Bombers from Radioactive Clouds Over a Simplified Target Area.

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DAMAGE TO AIRCRAFT: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
11	Air Ministry Science 2. Memo 272 (1957)	Secret	The Effect of Radioactive Fallout on the Operation of Fighter Airfields.

U.S. Reports DAMAGE TO AIRCRAFT: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	U.S.Naval Radiological Defence Laboratory. Report U.S.N./R.D.L.-362. August 1952. (M.O.D.Ref. No. 267) (T.I.L. Ref. P.60499) ACSIL 5613913.	Confidential/ Discreet	Radiological Factors Affecting the Operation of Aircraft in Atomic Warfare. Progress Report prepared for the Bureau of Aeronautics, Part A. For Part B (Secret) see DRB 54/15494.
2	U.S.N./R.D.L. Report No. 447 (M.O.D. Ref. No. 113)	Confidential/ Discreet	Proposed interim Operational Plan for the Tactical Decontamination of Carrier-Based Aircraft.
3	Naval Medical Research Institute, Bethesda. Report ADC-54 Revised. 10 March 1949. (M.O.D.Ref. No. 216)	Unclassified	Survey of Decontamination. 2 - Decontaminability of Aircraft Paints.
4	Wright Air Development Centre. Materials Lab. Report W.C.R.T.H.-M-5569. (M.O.D. Ref. Nos. 259 & 260)	Secret/ Discreet	Decontamination of Aircraft in Operation Buster.
5	Wright Air Development Centre. A.F.S.W.P.Report WT-535. March 1953. (M.O.D.Ref.Nos. 261 & 262)	Confidential/ Discreet	Operation Snapper. Project 6.5. Decontamination of Aircraft.
6	U.S.A.F. Ref. AF-WP-0-15 T.O. No. 000-110A-3. 4th August 1952. (M.O.D. Ref.Nos. 263 & 264)	Discreet	Decontamination of Radio-Active Aircraft - External Surfaces. (1952)

U.K. Reports

DAMAGE TO AIRCRAFT: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
1	Min. of Defence Tripartite Conference February, 1954. Section No. 4.	Secret/ U.K. Eyes Only	Thermal and Blast Effects on Aircraft
2	A.W.R.E. Report No. T28/58	Confidential	Operation Buffalo. Target Response Tests. Materials Group. Part 9C. Effects on Aircraft Wind Screens.
3	N.J. Hoff (Pergammon Press Ltd. London, 1958)	Unclassified	High Temperature Effects in Aircraft Structures. (Book)
4	RAE. Tech. Note. No. Mech. Eng. 251.	Confidential	Skin Temperature Rise in an Aircraft Exposed to Thermal Radiation from a Nuclear Explosion. Brinkworth.
5	RAE Tech. Note. No. Mech. Eng. 268.	Confidential	The Effects of Non Uniform Absorbtivity of Thermal Radiation from Nuclear Explosions on the Temperature rise in an Aircraft Skin. Brinkworth.
6	RAE. Tech. Memo. Arm 1726	Restricted	Notes on Radiation Reflected from a Plain Surface. Spring.
7	RAE. Test Note: Structures 1519	Confidential	Combined Transient Heating and Static Loading Tests of a Valiant Aileron. Naylor.
8	R.A.E. Report Mech. Eng. 21 21st Feb. 1959.	Confidential	Some Effects of the Environment on the Polar Distribution around the Delivering Aircraft of Thermal Radiation from a Nuclear Explosion. B. J. Brinkworth

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DAMAGE TO AIRCRAFT: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
1	Langley Aero Lab. N.A.C.A. Research Memo. L.55.B.03 NACA/TIB/4628	Confidential/ Discreet	An Investigation of the Effects of Rapid Skin Heating on Box Beams Loaded in Bending
2	Wright Air Development Centre, Tech. Report 52-216, 1953, (M.O.D. Ref. No. 250)	Confidential	Temperature Distribution in a Typical Aircraft Structure due to Transient External Heating. Vol. 2, B.36 aircraft.
3	Wright Air Development Centre, Tech. Report 52-217, 1953, (M.O.D. Ref. No. 251)	Confidential	The Effect of Non-Uniform Temperature Distribution on the Stresses in an Airplane.
4	Wright Air Development Centre, Tech. Report 53-210, 1953, (M.O.D. Ref. No. 252)	Confidential	Instrumentation for Measurement of Thermal Radiation at Operation Ivy.
5	Wright Air Development Centre, Tech. Report 54-103, 1953. (M.O.D. Ref. No. 253)	Confidential	Behaviour of Magnesium and Fibre-glass Panels subjected to Thermal Radiation.
6	Wright Air Development Centre, Tech. Report 53-209, 1953, (M.O.D. Ref. No. 254)	Confidential	Permanent Buckling of Sheet/Stringer Panels at Elevated Temperatures.

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DAMAGE TO AIRCRAFT: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
7	Wright Air Development Centre, Tech. Report No. 54-579, 1954. (M.O.D. Ref. No. 255)	Confidential	Analytical Studies of Aircraft Structures Exposed to Transient External Heating, Vol. 1. Thermal Response of a 'Thin' Plate under the Influence of a Constant Temperature Edge.
8	Wright Air Development Centre, Tech. Report No. 54-579, 1954. (M.O.D. Ref. No. 256)	Confidential	Analytical Studies of Aircraft Structures Exposed to Transient External Heating, Vol. 2. Thermal Response of a Finite Plate and the 'Thin' Plate Criterion.
9	Wright Air Development Centre, Tech. Report No. 54-579, 1955. (M.O.D. Ref. No. 257.)	Confidential	Analytical Studies of Aircraft Structures Exposed to Transient External Heating, Vol. 3. Thermal Response of the Skin and Support Flange of a Structural Joint.
10	Wright Air Development Centre, Tech. Report No. 55-192, 1955. (M.O.D. Ref. No. 258)	Confidential	Analytical Studies of Thermal Stresses on Aircraft Structures Exposed to External Heating, Vol. 1. Evaluation of the Thermal Response, Force and Moment in a Plate.
11	Wright Air Development Centre, Tech. Note 55-159 (M.O.D. Ref. No. 249)	Secret/Discreet	Aircraft Instrumentation for Special Weapons - Effects Tests.
12	Wright Air Development Centre. Tech. Report No. 54-384. Part 1. 15th October 1954. (M.O.D. Ref. No. 277)	Unclassified	The Effect of Thermal Radiation on Aircraft Structures. Part 1 - The M.I.T. Mk. 1 Radiant Heating Structural Test Facility.

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DAMAGE TO AIRCRAFT: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
13	Wright Air Development Centre. Tech. Report No. 54-103. (M.O.D. Ref. No. 373A)	Unclassified	Behaviour of Magnesium and Fibre glass Panels subjected to Thermal Radiation.

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DAMAGE TO AIRCRAFT: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
1	Min. of Defence Tripartite Conference February, 1954. Section No. 4.	Secret/ U.K. Eyes Only	Thermal and Blast Effects on Aircraft
2	A.W.R.E. Report No. T28/58	Confidential	Operation Buffalo. Target Response Tests. Materials Group. Part 9C. Effects on Aircraft Wind Screens.
3	N.J.Hoff (Pergammon Press Ltd. London, 1958)	Unclassified	High Temperature Effects in Aircraft Structures. (Book)
4	RAE. Tech. Note. No. Mech. Eng. 251.	Confidential	Skin Temperature Rise in an Aircraft Exposed to Thermal Radiation from a Nuclear Explosion. Brinkworth.
5	RAE Tech. Note. No. Mech. Eng. 268.	Confidential	The Effects of Non Uniform Absorbtivity of Thermal Radiation from Nuclear Explosions on the Temperature rise in an Aircraft Skin. Brinkworth.
6	RAE. Tech. Memo. Arm 1726	Restricted	Notes on Radiation Reflected from a Plain Surface. Spring.
7	RAE. Test Note: Structures 1519	Confidential	Combined Transient Heating and Static Loading Tests of a Valiant Aileron. Naylor.
8	R.A.E. Report Mech. Eng. 21 21st Feb. 1959.	Confidential	Some Effects of the Environment on the Polar Distribution around the Delivering Aircraft of Thermal Radiation from a Nuclear Explosion. B. J. Brinkworth

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DAMAGE TO AIRCRAFT: Blast

No.	Originator and Reference	Security Classification	Title
1	Min. of Defence Tripartite Conf. Feb. 1954, Section No. 4.	Secret/ U.K. Eyes Only	Thermal and Blast Effects on Aircraft.
2	A.W.R.E. Report T112/54.	Confidential	The Effects of Totem I Explosion on Aircraft of Stressed Skin Construction.
3	RAE Tech. Memo Aero/570	Confidential	Lethality Envelopes of the Airborne Aircraft due to Shock Waves from an Atomic Explosion.
4	AWRE Report T73/54	Secret	Operation Hurricane Group Reports Part 38. Structural Vulnerability of Aeroplanes to Blast from Atomic Bombs. Lessons Learnt from the Montebello Tests.
5	AWRE Report T72/54	Secret	Operation Hurricane Group Reports Part 37. The Behaviour of Aircraft Structures Under Blast From an Atomic Weapon.
6	AWRE Report T71/54	Secret	Operation Hurricane Group Reports Part 36. Report on the Installation of Aircraft Structures.

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DAMAGE TO AIRCRAFT: Blast

No.	Originator and Reference	Security Classification	Title
1	A.F.S.W.P. 1957 Tripartite Conf. Paper No. 4	Confidential/ Atomic	Aircraft Response Analysis and Test Procedures. Dehart.
2	U.S.A.F. Cambridge Res. Centre. Air Force Surveys in Geophysics No. 27	Secret	Lethal Gust and Overpressure Envelopes for the TU-4. Haskell.
3	Denver Research Inst. TIL P.46703	Confidential/ Discreet	A Damage Criterion for Comparison of High Explosives (Aircraft Target).
4	U.S. Army Ballistic Research Laboratories Memo. B.R.L. 866. November 1954. (M.O.D. Ref. No. 119)	Confidential/ Discreet	Damage to F6F Aircraft by External Blast. (8 lb and 100 lb charges).
5	A.F.S.W.P. Report I.T.R. 1433.	Confidential/ Discreet	In-Flight Structural Response of A4D1 Aircraft.
6	A.F.S.W.P. Report I.T.R. 1432.	Confidential/ Discreet	In-Flight Structural Response of FJ-4 Aircraft.
7	A.F.S.W.P. Report WT-1132.	Confidential/ Discreet	Destructive Loads on Aircraft in Flight.

U.K. Reports

DAMAGE TO AIRCRAFT: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T17/57	Confidential	Operation Buffalo: Target Response. Aircraft Group.
2	Min. of Defence Tripartite Conference February 1954. Section No. 4.	Secret/ U.K. Eyes Only.	Thermal and Blast Effects on Aircraft.
3	1957 Tripartite Conf. RAE. Report AWEC/P(57) 23.	Confidential	The Effect of Atomic Explosions on Parked Aircraft and Structural Targets at Operation Buffalo. S/L Turner.
4	1957 Tripartite Conf. A.M. Report AWEC/P(57)43	Secret/Atomic	Survey of the Vulnerability of Parked Aircraft to Nuclear Explosions, Henderson.
5	A.W.R.E. Report No. 28/58	Confidential	Operation Buffalo, Target Response Tests, Materials Group. Part 9C. Effects on Aircraft Wind Screens.
6	RAE. Memo. GW/59230/FIR.	Secret/Discreet	Nuclear Weapon Effects on Ballistic Missile Re-entry Heads.
7	A.W.R.E. Report T8/58	Confidential	Operation Antler. Target Response Group Effects on Swift Aircraft.
8	A.W.R.E. Report T47/58	Confidential	Operation Buffalo. The Effect of Atomic Explosions on Parked Aircraft and Aircraft Components. Part 2, Aircraft Components.
9	A.W.R.E. Report T66/57	Confidential	Operation Buffalo. The Effect of Atomic Explosions on Parked Aircraft and Aircraft Components. Part 1, Parked Aircraft.
10	Air Ministry. Science 2. Memo 220 (1953)	Secret	The Protection of Aircraft on the Ground from Atomic Attack.

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DAMAGE TO AIRCRAFT: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
11	Air Ministry Science 2. Memo 238 (1954)	Secret/Atomic	The Use of Atomic Bombs for the Attack of Bombers
12	Air Ministry Science 2. Memo 251 (1955)	Secret/Atomic	The Danger to a Valiant from Releasing a Nuclear Weapon at Low Altitude.
13	Air Ministry Science 2. Memo 286 (1958)	Secret	The Response of Aircraft, Runways and Radars to the Effects of Nuclear Explosions.

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DAMAGE TO AIRCRAFT: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	U.S.N./R.D.L.447 (M.O.D.Note No. 113)	Confidential/ Discreet	Proposed Interim Operational Plan for the Tactical Decontamination of Carrier-Based Aircraft.
2	U.S.N./R.D.L. 398 (M.O.D. Note No. 127)	Confidential/ Discreet	Decontamination Efficiencies at Various Levels of Initial Contamination on Glossy Sea-Blue Aircraft Lacquer.
3	U.S.N./R.D.L. (DRB 54/15494)	Secret	Radiological Factors affecting the Operation of Aircraft in Atomic Warfare. Progress Report Part B, 1952.
4	A.F.S.W.P. 1957 Tripartite Conference Paper No. 4.	Confidential/ Atomic	Aircraft Response Analysis and Test Procedures. Dehart.
5	Air Installations Division, H.Q. A.M.C.Wright-Patterson A.F.B. Report WT-88. May 1952. (M.O.D. Ref. No. 131)	Secret/ Atomic	Operation G reenhouse. Scientific Director's Report. Annexe 3,3 - U.S. Airforce Structures. Appendix 1 - Blast loading and Response of Structures. Section 2 - Structural Response. Armour Research Foundation Report on Nuclear Explosions, 1951.
6	Armour Research Foundation 15th July 1951. (M.O.D. Ref. No. 133)	Confidential/ Atomic	Operation Greenhouse. Interim Report. Scientific Director's Report.Annexe 3.3. - Airforce Structures Test. Vol. 3 - Blast loading and Response of Model Structures.
7	Armour Research Foundation. 15th July 1951. (M.O.D. Ref. No. 134)	Confidential/ Atomic	Operation Greenhouse. Interim Report. Scientific Director's Report. Annexe 3.3 - Vol. 4. Project 3.3. Appendix E, Vol. 3. Blast Loading and Response on Prototype Structures and Quarter scale Model.
8	U.S.N./R.D.L. Chemistry Dept. Report U.S.N./R.D. L.-452 23rd Dec. 1954. (M.O.D. Ref. No. 217)	Confidential/ Discreet	Countermeasure Performance Requirements for Carrier Air Operations after a Shallow Underwater Burst.

U.S. Reports — DAMAGE TO AIRCRAFT: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
9	Office of Naval Research. 1st August 1955. (M.O.D. Ref. No. 407/053/03/23) (M.O.D. Ref. No. 319)	Secret/Atomic	Fleet Air Defence Study
10	Chief of Naval Operations. Operations Evaluation Group. Study 541B. 1954. (M.O.D. Ref. No. 407/053/03 44) (M.O.D. Ref. No. 357)	Secret/Atomic	Effects of Carrier Spacings on the Expected Damage to Aircraft from Air Burst Atomic Bombs.
11	M.I.T. Department of Aeronautical Engineering. Paper AD.71541. (M.O.D. Ref. 385)	Unclassified	The Combined Effects of High Intensity Heating and Dynamic Loading on a One Cell Box Beam. M.Sc. Thesis by F. L. Williams, Jan. 17th 1955.

U.K. Reports

DAMAGE TO MILITARY FIELD EQUIPMENT: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. Report H12/52	Official Use Only	The Penetration of Gamma Radiation through the Walls of a Slit Trench.
2	ORS.B.A.O.R. Report 1/58.	Secret	The Requirements for Decontamination in the Corps and Divisional Areas and the Resources necessary to effect it.

No.	Originator and Reference	Security Classification	Title
1	Suffield Experiment Station. (Canada). Technical Paper 134.30 December, 1957. (T.I.L.Ref. P.72380)	Confidential	Deposit Patterns on Troops, Vehicles and Guns of 100 Mu glass Microspheres Sprayed from the Air. Watson and Deihl.

No.	Originator and Reference	Security Classification	Title
1	U.S. Chem. Corps. CRLR.326 (CD.7081)	Conf./Discreet	Interim Report. Experimental-Theoretical Attenuation of 1.2 Mev Gamma Radiation by Simple Structures.
2	A.F.S.W.P. Report WT.400	Confidential	"Operation Jangle". Project 6.2. Protection and Decontamination of Land Targets and Vehicles.
3	Rand Corpn. Memo. RM.1624. TIL P.60075	Military Use Only	Weight/Feasibility Calculation for Shielding of Truck Passengers. Harris.
4	Army Chemical Corps. Chemical and Radiological Labs. Report CRLR.297 1st August, 1953 (M.O.D. Ref. 83)	Secret/Discreet (C.C.)	Attenuation of 1.2 Mev Gamma Radiation by Soviet and U.S. Military Vehicles and U.S. Rail Equipment.
5	Army Board No. 2CONARC. Fort Knox. Report of Project NR-1846. (M.O.D.Ref. No.167)	Confidential/ Discreet	Report of Test of Tactical Dosimeters (Continental Army Command) (Tentative Edition)

U.K. Reports

DAMAGE TO MILITARY FIELD EQUIPMENT: Thermal Radiation (See also Section 9.3)

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. Report T28/58	Confidential	Operation Buffalo. Target Response Tests, Materials Group. Part 9(a). Effects on Chemical Warfare Equipment.

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DAMAGE TO FIELD EQUIPMENT: Blast

No.	Originator and Reference	Security Classification	Title
1	W.O. Report AWEC/P(57)18	Secret/Atomic	Blast Tests on Military Equipment at Operation Buffalo. Drake-Seager.
2	A.W.R.E. Report T75/54.	Secret	Effects of the Totem Explosions on Field Defences.
3	A.W.R.E. Report T84/54	Confidential	The Effects of an Atomic Explosion upon Ammunition at Operation Totem.

No.	Originator and Reference	Security Classification	Title
1	U.S. Reports Armour Research Foundn. Tech. Memo. ORO-T-224 SA/AC Library No. 16435	Secret/ Discreet Security Information	Analysis of Atomic Weapons Effects upon Army Ground Operations Equipment. Vol.2. Effects of Thermal Radiation.
2	U.S.N.R.D.L. Report TR-101 11th August, 1955. (TIL Ref. P67803) (ACSIL/57/3418)	Unclassified	Thermal Vulnerability of Military Installations. Broido and Trilling.

U.S. Reports

DAMAGE TO MILITARY FIELD EQUIPMENT: BLast

No.	Originator and Reference	Security Classification	Title
1	U.S. AFSWP Report	Confidential	Effects of Blast on Military Field Equipment. Hesse.
2	Operation Research Off. Tech.Memo. ORO-T-223 (DRP 55/6184)(TIL P59622) (M.O.D. Ref. No. 329)	Secret	Analysis of Atomic Weapons Effects upon Army Ground Operation Equipment, Vol.1, Blast Effects.
3	U.S. (M.O.D.Ref. No. 369) (M.O.D.Ref.407/053/03)	Secret/Atomic	Conference Agenda. The Effects of Blast on Military Field Equipment. February, 1956.
4	C.E.T.G. Interim Report I.T.R.1408 (M.O.D. Ref. No. 378)	Confidential	Operation Plumbbob. Project 1.8B. Effects of Rough Terrain on Drag-Sensitive Targets.
5	AFSWP Report WT-313	Confidential 1958	Operation Buster 1951. Project 3.5. Minefield Clearance. Thurston and Bardeen.
6	AFSWP Report WT-526	Confidential 1958	Operation Snapper 1952. Project 3.4. Minefield Clearance. Richmond.
7	AFSWP Report WT-370	-	Operation Upshot/Knothole 1954. Project 3.18. Minefield Clearance. Richmond.
8	AFSWP Report ITR-1435	Secret	Operation Plumbbob 1957. Project 6.1. Minefield Clearance.
9	E.R.D.L. Fort Belvoir Virginia Report 1468-TR 2nd November, 1956	Secret/ Restricted Data	Field Fortifications Test Exercises. Desert Rock VI. N.J. Davis Jr.

U.K. Reports

DAMAGE TO MILITARY FIELD EQUIPMENT: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
20	A.W.R.E. Report T30/58	Confidential/ Discreet	Operation Buffalo. Ordnance Group. Part 3 - Details of Exposure of 'B' Vehicles.
21	A.W.R.E. Report T41/58 November, 1958	Confidential/ Discreet	Operation Buffalo, Target Response Tests. Ordnance Group, Part 4(a) Details of Exposure of Field Guns and Mortars.
22	A.W.R.E. Report T48/58 February, 1959	Confidential/ Discreet	Operation Buffalo, Target Response Tests. Part 4(b) A.A. Guns and Rifles.
23	M.O.S., F.V.R.D.E. Report BR 149 March, 1958.	Secret/Discreet	Nuclear Radiation Effects on Armoured Fighting Vehicles.
24	Tri. Conf. on Weapons Effects 1957 Paper AWEC/P(57)18	Secret/Atomic	Blast Tests on Military Equipment at Operation Buffalo. E.R. Drake Seager.

U.K. Reports

DAMAGE TO MILITARY FIELD EQUIPMENT: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T84/54	Confidential	The Effects of an Atomic Explosion upon Ammunition, November, 1956.
2	A.W.R.E. T5/57	Confidential	Operation Buffalo: Target Response. Explosive Group.
3	A.W.R.E. T25/57	Confidential	Operation Buffalo: Target Response. Ordnance Group.
4	War Office, Operation Totem, 1953, Army Equipment Group	Secret	Interim Summary of Trials Results prepared for D.A.W.R.E.
5	A.W.R.E. T77/54	Confidential	Effects on Respirators, Anti-Gas.
6	A.W.R.E. T81/54	Confidential	The Effect of an Atomic Explosion on Medical Equipment.
7	A.W.R.E. T82/54	Secret	The Effect of an Atomic Explosion on Communications in the Field.
8	A.W.R.E. T83/54	Confidential	The Effect of an Atomic Explosion on Royal Artillery Equipment.
9	A.W.R.E. T78/54	Secret/Atomic/ U.K. Eyes Only	Operation Totem. The Effects of an Atomic Explosion on a Centurion Tank. Vols. 1 and 2.
10	War Office (GS(W)11)2 57/Misc/9213	Confidential	Operation Buffalo. War Office Atomic Trials Team. Outline Report.

U.K. Reports

DAMAGE TO MILITARY FIELD EQUIPMENT: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
11	A.W.R.E. Report T16/57	Confidential	Operation Buffalo: Target Response Tests - Effects on Communication Cables. Lt. Col. Brenchley.
12	W.O. Report AWEC/P(57)19	Confidential	Communication Cables at Operation Buffalo, 1956. Lt. Col. Brenchley.
13	A.W.R.E. Report T28/58	Confidential	Operation Buffalo. Target Response Tests. Materials Group. Part 9A. Effects on Chemical Warfare Equipment.
14	A.O.R.G. Report No. 4/58	Secret/Discreet	The Vulnerability of Armoured Fighting Vehicles and their Crews to Nuclear Weapons.
15	A.R.D.E. Memo (B) 1/58	Confidential	The Effects of Atomic Weapons on Ammunition. 1 - Unguided Rockets.
16	A.W.R.E. Report T7/58	Confidential	Operation Buffalo. Explosives Group Final Report Part 1. Introduction.
17	A.W.R.E. Report T10/58	Confidential	Operation Buffalo. Materials Group Part 8B. The Effect of a Nuclear Explosion on Jerrican Stacks.
18	A.W.R.E. Report T14/58	Confidential Discreet C.C.	Operation Buffalo. Ordnance Group Part 1. General Introduction.
19	A.W.R.E. Report T20/58	Confidential	Operation Buffalo. Explosives Group. Final Report Part 2. Mines.

No.	Originator and Reference	Security Classification	Title
7	Operations Research Office. Johns Hopkins University Tech. Memo. ORO-T-138.7 Jan. 1952. (M.O.D. Ref. No. 104)	Confidential/ Discreet	Army Supply Installations as Tactical Atomic Bomb Targets.
8	Operations Research Office. Johns Hopkins University Report ORO-R-2 (FEC) 1st May, 1951. (M.O.D. Ref. No. 105)	Secret/Discreet	Tactical Employment of Atomic Weapons. A Study of situations which arose in Korea from the view point of their suitability as Nuclear Targets.
9	M.I.T. Report of 15th July, 1951. (M.O.D. Ref. No. 132)	Confidential/ Atomic	Operation Greenhouse. Interim Report. Scientific Director's Report Annexe 3.1. Vol.II - Army Structures Test. Appendix 7. Permanent Effects.
10	A.F.S.W.P. Report WT-1181	Official Use Only	Operation Tea Pot. Projects 36.1 and 36.2. Exposure of Mobile Homes and Emergency Vehicles to Nuclear Explosions.

Miscellaneous Reports. DAMAGE TO NAVAL AND MARITIME STRUCTURES Nuclear Radiation, Contamination and Decontamination.

No.	Originator and Reference	Security Classification	Title
1	Canada. Dept. of National Defence (Army) Report 19/55 (CD.9781)	Confidential	Naval Test of Radiation Detection Equipment.

U.K. Reports. DAMAGE TO NAVAL AND MARITIME STRUCTURES. Nuclear Radiation, Contamination and Decontamination.

No.	Originator and Reference	Security Classification	Title
1	Admiralty Research Lab. Report R2/C.747.	Confidential	Evaluation of the Washdown Effectiveness of a Ship's Pre-wetting.
2	A.W.R.E. T109/54	Confidential/ Atomic	Radiochemical Decontamination Experiments on Naval Construction Materials I. Evaluation of Pre-wetting.
3	A.W.R.E. T110/54	Confidential	Radiochemical Decontamination Experiments on Naval Construction Materials II. Experiments on Contaminated Dry Samples.
4	1957 Tripartite Conf. Report AWEC/P(57)215.	Secret	The Protection Afforded by a Ship's Structure against the Gamma Radiation emitted by an Atomic Explosion.
5.	Engineer in Chiefs Dept. Admiralty, December, 1957. E-in-C/TP.52(ACSIL/ADM/ 58/94.)	Confidential	Fall-out from Nuclear Explosions. Probable effects on Engineering Departments of H.M. Ships.
6	ARL/N1/C743 July, 1958.	Unclassified	Contamination of Ships Weather-work by Muddy Radioactive Fallout. E. W. Jackson.
7	ARL/N2/C763	Unclassified	Techniques for the Decontamination of Ships and Personnel. Jackson.
8	11th Tri. Conf. on Tox. Warfare U.K. Paper 11-TRI-C98.	Confidential	Pre-Wetting of Ships Under Arctic Conditions.
9	ARL/R1/R650 July, 1956.	Secret	Gamma Radiation Measurements in the Boiler Control Post of H.M.S. Royalist from Simulated Radioactive Contamination in the Boiler Rooms.

U.K. Reports DAMAGE TO NAVAL AND MARITIME STRUCTURES. Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
10	ARL/R1/R651 Sept. 1956.	Secret	The Sheltering Afforded by H.M.S. Ships Against Gamma Radiation Emitted from Radioactive Surface Contamination. A Preliminary Report.
11	ARL/N1/C748 Oct. 1957.	Unclassified	Underwater Gamma Probe: Possible Use for Monitoring Contamination Entering Condenser and Other Inlets. D. M. C. Thomas.

U.S. Reports. DAMAGE TO NAVAL AND MARITIME STRUCTURES. Nuclear Radiation, Contamination and Decontamination.

No.	Originator and Reference	Security Classification	Title
1	U.S.N./R.D.L.447 (M.O.D. Note No.113)	Confidential/ Discreet	Proposed Interim Operational Plan for the Tactical Decontamination of Carrier -Based Aircraft.
2	U.S. Govt. Printing Office (CD.3030)	Unclassified	Cooling-off Ships too Hot to Handle.
3	U.S.N./R.D.L. RDL/TR-10 (NS.086001)	Unclassified	Preparation of Simulants for Contaminants Produced by Nuclear Detonations in Harbours.
4	A.F.S.W.P.Report I.T.R.-927 (M.O:D.Ref.No.175).	Secret/Discreet	Operation Castle. Project 6.4. Proof Testing of Atomic Weapon Ship Countermeasures, 1954.
5	U.S.N.R.D.L. Report of November, 1957. (M.O.D. Ref.No.339).	Unclassified	Radiological Recovery of Ships. Draft for Chapter 89 of BuShips Manual.
6	U.S.N.R.D.L. Report. (T.I.L. Ref.P.68879)	Confidential/ Discreet	Efficiency of a Contact Water Curtain in Preventing or minimising contamination. 1950.
7	USN/RDL-TR-130 (NS 086-001 Jan. 22nd 1957.)	Unclassified	Relative Decontamination of Clean and Artificially Soiled Navy Grey Paint Surfaces. J. L. Mackin.

U.K. Reports. DAMAGE TO NAVAL AND MARITIME STRUCTURES. Damage by Blast and Water Waves.

No.	Originator and Reference	Security Classification	Title
1	Atomic Bomb Trials (Operation Cross Roads) Parts 1 and 2. C.B.004467A and Annexures C.B.004467B. 1946.	Secret	Report of the British Services Observer at Bikini Atoll.
2	N.C.R.E. Report No.R.330	Secret	Some Experiments on Ships' Funnel Models subjected to Air Blast Loading, May, 1957.
3	Cole, R.H.	Unclassified	Underwater Explosions (Book)
4	A.R.E. Report 1/48. January, 1948.	Secret	The Physical Effects of Atomic Weapons, Part 1. Damage to Ships of Underwater Explosions of Atomic Bombs. Penney.
5	N.C.R.E. Report No.R.406	Confidential/ Discreet	The Effect of Refraction of the Pressure Pulse from Underwater Atomic Explosions, Haywood.
6	N.C.R.E. Report No.R.332.	Unclassified	The Response of an Elastic Cylindrical Shell to an Underwater Explosion. Haywood.

U.S. Reports. DAMAGE TO NAVAL AND MARITIME STRUCTURES. Damage by Blast and Water Waves.

No.	Originator and Reference	Security Classification	Title
18	Tech. Report No.12 CV-12-54-ONR-266 (08)-CE Sept.1954.	Unclassified	Dynamic Buckling of Submerged Plates and Shells. Bleich and Dimaggio.
19	Tech. Report No.6 B.11-6/22 Nov. 1951.	Confidential	Analysis of Large Plastic Deformations in Jacknifing of a Submarine Pressure Hull. P. S. Symonds.
	UERD Report 9-56	Confidential	Model Studies on Effects of Underwater Atomic Explosions on Ships. Part 1. Development of a Cargo Ship Model. W. W. Murray.
20	Nav.Ord. Report 3912 Feb. 1955.	Secret	Some Estimated Damage Ranges for Kiloton Weapons Used Against Mk.25 and Mk.39 Mines Rosenbaum.
21	Nav.Ord. Report 2987 AFSWP.484 May, 1954.	Confidential/ Discreet	The Scaling of Base Surge Phenomena of Shallow Underwater Explosions. Milligan and Young.

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No.	Originator and Reference	Security Classification	Title
1	Atomic Bomb Trials (Operation Cross Roads) Parts 1 and 2. C.B.004467A and Annexures C.B.004467B. 1946.	Secret	Report of the British Services Observer at Bikini Atoll.
2	N.C.R.E. Report No.R.330	Secret	Some Experiments on Ships' Funnel Models subjected to Air Blast Loading, May, 1957.
3	Cole, R.H.	Unclassified	Underwater Explosions (Book)
4	A.R.E. Report 1/48. January, 1948.	Secret	The Physical Effects of Atomic Weapons, Part 1. Damage to Ships of Underwater Explosions of Atomic Bombs. Penney.
5	N.C.R.E. Report No.R.406	Confidential/ Discreet	The Effect of Refraction of the Pressure Pulse from Underwater Atomic Explosions, Haywood.
6	N.C.R.E. Report No.R.332.	Unclassified	The Response of an Elastic Cylindrical Shell to an Underwater Explosion. Haywood.

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No.	Originator and Reference	Security Classification	Title
1	Columbia University Dept. of Civil Engineering & Engineering Mechanics Technical Report No.19 November 1956.	Unclassified	Initial Velocity in Shells on a Free Surface due to a Plane Accoustic Shock Wave. (Office of Naval Research Contract No. 266(08)). Baron and Bleich.
2	Columbia University, Dept. of Civil Engineering Technical Report No.10 1953.	Unclassified	Further Studies of the Response of a Cylindrical Shell to a Transverse Shock Wave. (Office of Naval Research Contract No. 266(08)). Baron and Bleich.
3	Trans. Institution Naval Architects. Vol. 98 Page 443, 1956.	Unclassified	Deformation of Metal Panels and Plates. Clarkson.
4	Underwater Explosions Research Division. Norfolk Naval Shipyard Report 17-49.	Confidential/ Discreet	Afterflow and Re-loading.
5	Underwater Explosions Research Division, Report 19-56. December 1956.	Confidential/ Discreet	Introduction to Underwater Explosion Research. Keil.
6	Underwater Explosions Research Division, Report 1-57, January 1957.	Confidential/ Discreet	Model Studies on Effects of Underwater Atomic Explosion on Ships. Part 2 - A Selection of Measurements made in Cargo Ship Model Tests. Murray.
7	Brown University R.I.Contract N70 No.35810 Technical Report No.16 1953.	Unclassified	On the Interaction of Elastic Shells and Acoustic Waves. Carrier and Ross.
8	Fifth Symposium on Progress in Underwater Explosion Research. NavShips Report 1953-3 Ref.250-423-22.	Confidential/ Discreet	The Calculated Response of a Submerged Cylindrical Shell to an Exponential Pressure Pulse. Sette et al.

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No.	Originator and Reference	Security Classification	Title
9	Underwater Explosion Research Division Report 1-55, Jan.55.	Unclassified	The Interaction of a Cylindrical Acoustic Wave with a Beam of Circular Cross Section. Murray.
10	T.M.B.Report No.940,June.55	Unclassified.	Collapse Pressures of Metal Panels and Plates. Greenspon.
11	David Taylor Model Basin Report C-616	Secret/Discreet	Damage to Stiffened Cylinders under Scaled Atomic Bomb Attack. Sette and Gooding.
12	David Taylor Model Basin Report C-680	Confidential/ Discreet	A second investigation on Damage to Stiffened Cylinders under Scaled Atomic Bomb Attack. Sette and Gooding.
13	Underwater Explosion Research Division. Norfolk Naval Shipyard Report 10-56	Confidential/ Discreet	A New Lethal Stand-off Formula for Submerged Submarines. Schauer.
14	Underwater Explosion Research Division, Norfold Naval Shipyard Report 16-56.	Secret/Discreet	On the Prediction of the Hull-Splitting Stand-off of Submarines from Atomic Depth Charges. Keil and Schauer.
15	Underwater Explosion Research Division. Report F-17-53.	Secret/Discreet	Lethal Radius of the Atomic Bomb for Submarines. Keil.
16	Office of Naval Research. Underwater Explosion Research Vol. III. The Damage Process.	Unclassified	Theoretical Investigation of Cavitation Phenomena occuring when an Underwater Pressure pulse is incident on a yielding sufface.
17	UERD Report 18-56	Confidential	Tapered Charge Tests Against 1/35-Scale Surface Ship Models. Murray.

U.K. Reports DAMAGE TO NAVAL AND MARITIME STRUCTURES: Damage by Combined Effects.

No.	Originator and Reference	Security Classification	Title
1	Admiralty ARL/R1/AW 50	Secret/Discreet	The effect of a 10 magaton Weapon on a Fleet at Anchor in Scapa Flow.
2	Supt.Admiralty, Materials Laboratory SSF/41/55/1/5	Secret	Minute dated 10/55 to Chief of Amphibious Warfare.
3	N.C.R.E. Note dated Feb. 1956. (M.O.D. Ref.No. 207)	Secret/Discreet U.K. Eyes Only.	Operation Wigwam - U.S. Atomic Depth Charge Explosion, May, 1955. A.R. Bryant.
4	ARL/R4/C791 Sept. 1957.	Secret	Operation Mosaic. Final Report on Naval Measurements.
5	Home Office Report CD/SA51	Confidential	Assumed Effects of Two Atomic Bomb Explosions in Shallow Watter Off the Port of Liverpool.

Miscellaneous Reports DAMAGE TO NAVAL AND MARITIME STRUCTURES: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	N.A.T.O. (CD.9643)	Confidential	The Vulnerability of Dock Gates Subjected to Atomic Attack.

U.S. Reports DAMAGE TO NAVAL AND MARITIME STRUCTURES: Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
7	U.S. Navy Bureau of Yards & Docks. A.F.S.W.P.Report WT-729, May 1955 (Cut) (M.O.D. Ref.No.325)	Confidential/ Atomic	Operation Upshot Knothole 1953 Projects 3.11 - 3.16. Navy Structures. 3.11 Steel Warehouses. 3.12 Brick Constructions 3.13 Gable Shelters and Torque Tube Panel 3.14 Precast Warehouses. 3.13, 3.15 Effects of Earth Cover 3.16 Windows and Glazing.
8	Chief of Naval Operations Operations Evaluation Group Study 508-B (M.O.D. Ref. No.356) (M.O.D. Ref.No. 407/053/03/43)	Secret/ Atomic	Effectiveness of Atomic Weapons against a Fast Carrier Task Group (1953)
9	Chief of Naval Operations, Operations Evaluation Group. Study 541-B. (M.O.D.Ref.No.407/053/03/44) (M.O.D. Ref.No.357)	Secret/ Atomic	Effects of Carrier Spacings on the Expected Damage to Aircraft from Air Burst Atomic Bombs (1954)
10	Chief of Naval Operations Operations Evaluations Group Study 547-B (M.O.D. Ref.No.358) (M.O.D.Ref.No. 407/053/45)	Secret/ Atomic	Effects of High Yield Weapons on Ship Formations.
11	U.S.N.R.D.L. Report ADO-110. 22 April 1949 (M.O.D. Ref.No. 367)	Unclassified	Physical Damage to Ships and Marine Installations.

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No.	Originator and Reference	Security Classification	Title
1	A.F.S.W.P. 1957 Tripartite Conf. Paper No. 8.	Confidential/ Atomic	Ship Damage and Criterion, including Underwater Phenomena. Focke.
2	U.S. Naval Ordnance Laboratory Report Nav.Ord. 2987. A.F.S.W.P. Report 484, 1st May, 1954. (Mod. Ref. No.86)	Confidential/ Discreet	The Scaling of Base Surge Phenomena of Shallow Underwater Explosions.
3	A.F.S.W.P. Report I.T.R.-927 (MOD Ref.No. 175)	Secret/Discreet	Operation Castle, Project 6.4. Proof-testing of Atomic Warfare Ship Countermeasures (1954).
4	A.F.S.W.P. Report WT.774 (MOD Ref.No. 77)	Confidential/ Atomic	Operation Upshot-Knothole, Project 8.11A. Incendiary Effects on Building and Interior Kindling Fuels, 1953. Report by U.S. Department of Agriculture Forest Service, Forest Products Labatory.
5	U.S.N.R.D.L. Chemistry Department Report U.S.N.R.D.L.- 452 23rd December, 1954. (MOD. Ref.No. 217)	Confidential/ Discreet	Countermeasure Performance Requirements for Carrier Air Operations after a Shallow Underwater Burst.
6	Office of Naval Research Paper dated 1 Aug.1955, (MOD. Ref.No. 319 and No.407/053/03/23)	Secret/Atomic	Fleet Air Defence Study.

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DAMAGE TO STRUCTURES ON LAND : Nuclear Radiation, Contamination, and Decontamination

No.	Originator and Reference	Security Classification	Title
1	U.S. Dept. of Navy, Navdocks TP-PL-13 U.S. Army, TM 3-225	Unclassified	Radiological Recovery of Fixed Military Installations. (Interim Revision, 16th April, 1958)
2	A.F.S.W.P. Report WT-400	Confidential	Operation Jangle. Project 6.2. Protection and Decontamination of Land Targets and Vehicles.
3	U.S.N./R.D.L. Report ADL. 55, December, 1948 (M.O.D. Ref. No. 366)	Unclassified	Military Decontamination of Shore Installations (19/10).
4	Naval Research Lab. Report 4886, March 28, 1957	Unclassified	Fall-out Protection Afforded by Standard Enlisted Men's Barracks. Malich, C.W. and Beach, L.A.

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DAMAGE TO STRUCTURES ON LAND : Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T20/54	Secret	Penetration of Gamma Flash into Anderson Shelters and Concrete Cubicles.
2	C.D.E.E., Porton Tech. Paper (R)15, September, 1958.	Restricted	Radiological Decontamination : an Investigation of the Absorption of Fission Isotopes into Concrete. H. Stretch.
3	A.W.R.E. Report T31/58	Confidential	Operation Buffalo. The Attempted Decontamination of Roofs by Wash-down.

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DAMAGE TO STRUCTURES ON LAND : Thermal Radiation

No.	Originator and Reference	Security Classification	Title
1	RFN.567, January, 1950 (M.O.D. Ref. No. 304)	Secret	Investigation of Fire Damage Caused by the Atomic Bombs on Hiroshima and Nagasaki, by J. B. Hawker, and O.C. Young of the British Mission to Japan.
2	U.S.N./R.D.L. Report TR-101 1955 (T.I.L. Ref. P.67803)	Unclassified	The Thermal Vulnerability of Military Installations. Broido and Trilling.
3	U.S. Civil Defence Administration Film. (Home Office Film Library)	Unclassified	The House in the Middle.

DAMAGE TO STRUCTURES ON LAND : Thermal Radiation

No.	Originator and Reference	Security Classification	Title
1	A.R.E. Report No. 1/48 Part 20	Secret	The Risk of Fires from Fractured Oil Tanks and Pipelines by Radiation from an Atomic Bomb.
2	Fire Research Station S.R. Note No. 28/1956	Confidential	Heat Radiation Shields for Defence Against Atomic Explosions. Simms et al.
3	Fire Research Station F.R. Note No. 280/1956	Unclassified	The Effect of Moisture Content on the Spontaneous Ignition of Wood by Radiation. Thomas et al.
4	Fire Research Station F.R. Note No. 305	Unclassified	The Influence of External Air Movements on the Ignition of Materials by Radiation. Simms.
5	Fire Research Station F.R. Note No. 308/1957	Unclassified	The Effects of Absorptivity on the Ignition of Materials by Radiation Simms et al.
6	Home Office Report CD/SA 21	Secret	The Zoning of Points for Fire Susceptibility.
7	"Wood", March, 1953, pages 93-95. April, 1953, Pages 134-137 May, 1953, pages 176-177	Unclassified	Fire Retardant Paints. Hird, D. and Simms, D.L.
8	Home Office Report CD/SA 6	Secret	The Atomic Bomb as a Fire Raiser - A Study of the Mechanism of Initiation and Development.

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DAMAGE TO STRUCTURES ON LAND : Blast

No.	Originator and Reference	Security Classification	Title
49	CD.11074 Fitzwilliam House, Cambridge, December, 1956.	Unclassified	The Ultimate Strength of Concrete Panels subjected to Uniformly Distributed Loads. Powell, D.S.
50	A.W.R.E. Report E1/57	Confidential	Incident Stress on Buried Shelters from Megaton Bombs.
51	A.W.R.E. Report E5/57	Confidential	Investigation of Static Strength and Resistance to Air Blast of 1/10 Scale Trench Shelter Roof Slabs.

Miscellaneous Reports

DAMAGE TO STRUCTURES ON LAND : Blast

No.	Originator and Reference	Security Classification	Title
1	Revue Universelle des Mines. 8e Serie Tome II No.7 (1935)	Unclassified	Analysis of Deformation by the Semi-Graphical (or Phase Plane) Method. Lamoen, J.
2	Ingeniorvidenskabelige Skriftn. 1936. Copenhagen	Unclassified	"Wind Pressure on Buildings", Experimental Researches (Second Series) Irminger Jov and Nkkentved, C.

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DAMAGE TO STRUCTURES ON LAND : Blast

No.	Originator and Reference	Security Classification	Title
32	M.O.S.(H.E.R.) Report H9/53	Confidential	Model Experiments on the Entry of Blast into Type S1, Grade A Surface Shelters. II. The Effect of Varying Incident Shock Pressure.
33	M.O.S.(H.E.R.) Report H10/53	Confidential	Model Experiments on the Entry of Blast into Type S1, Grade A Surface Shelters. III. The Effect of Varying the Size of the Doorway Aperture and of a Revolving Door.
34	A.W.R.E. Report O-16/56	Confidential	An Electrical Analogue of the Pressure Changes Inside Air Raid Shelters when Subjected to a Blast Pressure Wave.
35	M.O.S.(H.E.R.) Report H13/53	Official Use Only	The Propagation of Blast in Pipes and Tunnels.
36	M.O.S.(H.E.R.) Report H7/52	Confidential	The Penetration of Blast into a Tunnel. Part I. Dependence on Charge Position.
37	M.O.S.(H.E.R.) Report H15/52	Confidential	The Penetration of Blast into a Tunnel. Part II. Variation of Peak Overpressure along the Tunnel.
38	Ministry of Works Inter-Departmental Structural Precautions Advisory Committee, S.P.A.(56)3, 1956.	Secret	The Results of Static Tests on Reinforced Concrete Panels.
39	A.W.R.E. Report T66/54	Confidential	Examination by Ministry of Works of the Performance of Reinforced Concrete Cubicles at Operation Hurricane.
40	A.W.R.E. Report T87/54	Confidential	Civil Defence Structures at Operation Totem.

No.	Originator and Reference	Security Classification	Title
41	Civil Defence (Inter-Departmental) Structural Precautions Research Committee, CD/SPR/86, March, 1951.	Secret	Tests of the Transverse Loading of Brick Panels.
42	D.S.I.R. Road Research Laboratory, Note No. ARP/60/DJM, July, 1940	Unclassified	Tests of the Transverse Loading of Brick Panels.
43	D.S.I.R. Building Research Station, Defence Report No. 31, 1953.	Restricted	Tests of the Transverse Loading of Brick Panels.
44	D.S.I.R. Building Research Station, Report No. 2468, June, 1951.	Unclassified	Racking Load Tests on a Concrete Encased Steel Frame.
45	D.S.I.R. Building Research Station, Defence Report No.34, 1953.	Restricted	Racking Load Tests on a Concrete Encased Steel Frame.
46	A.R.E. Shoeburyness Lab. Note 14/50.	Secret	The Effect of Blast on a Building from a 20 KT Charge.
47	Trans.Institution Naval Architects. Vol. 98 Page 443, 1956.	Unclassified	Deformation of Metal Panels and Plates. Clarkson, J.
48	Building Research Station Note B180, December, 1957	Restricted	The Measurement of Sonic Bangs and their Effect on Typical Buildings. Newberry, C.W.

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No.	Originator and Reference	Security Classification	Title
11	A.W.R.E. Report T6/57	Confidential	Operation Buffalo : Interim Report. Target Response. Structures Group. L.C. Davies.
12	A.W.R.E. Report T46/57	Confidential	The Effect of Blast on Reinforced Concrete Slabs and the Relationship with Static Loading Characteristics.
13	A.W.R.E. Report T47/57	Confidential	The Effect of Earth Covers on the Resistance of Shelter Roofs.
14	A.M. Report AWEC/P(57)35	Secret/Atomic	The Vulnerability of Airfield Runways to Nuclear Explosions. Henderson.
15	A.W.R.E. Report E7/56	Confidential	Static Load Deflection Tests on 1/10th Scale Reinforced Concrete Square Slabs Designed as Test Pieces for Operation Buffalo.
16	A.W.R.E. Report E8/56	Confidential	Investigation of Blast Loading on the Damage Sustained by 1/10th Scale Reinforced Concrete Panels.
17	Civil Defence Joint Planning Staff, Paper C.D. J.P.S.(E.A.) (48) 14 (Revised)	Unclassified	Method for Estimating Damage by Blast to British Houses.
18	A.W.R.E. Report H3/51	Restricted	Static Demolition of a Farmhouse.
19	Tripartite Conference, 1954, Paper Z.8	Unclassified	Cratering and Earth Shock.
20	Cambridge University Press	Unclassified	Introduction to the Theory of Seismology. Bullen, K.E.
21	A.W.R.E. Report E2/53	Confidential	The Deflection of Plain Wall Panels by Atomic Blast.
22	A.W.R.E., Foulness Laboratory, Note 1/54	Confidential	Investigation into the Ratio between the Average and Central Deflections of a Model Wall Panel.

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No.	Originator and Reference	Security Classification	Title
23	A.W.R.E. Report E4/55	Confidential	Model Studies of the Reinforced Concrete Structures used in the Montebello Atomic Bomb Trials.
24	Building Research Board Special Report No.3, H.M.S.O., 1921.	Unclassified	Report of a Research on the Strength of Thin Walls. Dr. O. Faber.
25	A.W.R.E. Report T17/54	Secret	Operation Hurricane Group Reports : Anderson Shelters.
26	D.S.I.R. Road Research Laboratory, Note No. ARP/30/FGT, March, 1940.	Unclassified	Tests of the Transverse Loading of Brick Panels.
27	A.W.R.E. Report E5/55	Secret/Discreet	Loading of Buildings by a Large Scale Blast Wave. I. A Survey of Available Information and the Development of an Empirical Method of Calculating the Loading on the Wall Facing the Blast.
28	Civil Engineering, Vol.10 March, 1940.	Unclassified	Wind Pressure on Structures. Howe, G.E.
29	A.W.R.E. Report E2/55	Confidential	Model Experiments on the Loading of the Individual Plain Wall Panels on a Four Storey Block of Flats due to Atomic Blast.
30	A.W.R.E. Report E11/57	Confidential	Loading of Buildings by a Large Scale Blast Wave. II. The Development of an Empirical Method of Calculating the Loading on the Wall Facing Away from the Blast.
31	M.O.S.(H.E.R.) Report /H22/52	Confidential	Model Experiments on the Entry of Blast into Type S1 Grade A Surface Shelters. I. The Effect of Different Arrangements of Blast Wall on the Pressure Inside the Shelter.

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No.	Originator and Reference	Security Classification	Title
65	A.F.S.W.P. Report ITR-1459	Official Use only	Operation Plumbbob. Project 31.4. Evaluation of Industrial Doors subjected to Blast Loading.
66	A.F.S.W.P. Report ITR-1460	Official Use only	Operation Plumbbob. Project 31.5. Test and Evaluation of Anti-Blast Valves for Protective Ventilating Systems.
67	A.F.S.W.P. Report ITR-1474	Official Use only	Operation Plumbbob. Project 34.3. Test of Buried Structural-plate Pipes subjected to Blast Loading.
68	A.F.S.W.P. Report ITR-1475	Official Use only	Operation Plumbbob. Project 34.4. Blast Effects on Air cleaning system.
69	A.F.S.W.P. Report ITR-1507	Official Use only	Operation Plumbbob. Project 33.6. The Internal Environment of Underground Structures subjected to Nuclear Blast. 11 - Effects on Mice located in Heavy Concrete Shelters.
70	A.F.S.W.P. Report WT-1461	Official use only	Operation Plumbbob. Project 38.1. - II - Blast Effects on Glass Vacuum Containers.
71	E.R.D.L. Fort Belvoir Virginia Report 1468-TR 2nd November, 1956.	Secret/ Restricted Data	Field Fortifications Test Exercises. Desert Rock VI. N. J. Davis Jr.
72	USAEC Report WASH-182 May, 1954.	Unclassified	The Effects of Atomic Bomb Blast on Elevated Tanks and Standpipes.

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No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. Report E5/56	Secret	High Explosive Blast Tests on Experimental Blast Traps Designed by the Ministry of Works.
2	A.W.R.E. Report E2/57	Confidential	Damage sustained by 1/10th Scale Reinforced Concrete Surface due to Air Blast. O'Brien and Carter.
3	A.W.R.E. Report E10/57	Confidential	An Investigation on the Behaviour of 1/10th scale Model Heavy Girder Bridges under Blast Loading.
4	1957 Tripartite Conf. A.W.R.E. Report E8/57	Confidential	Further Experiments on the Effects of Shielding a Building from Atomic Blast
5	1957 Tripartite Conf. A.W.R.E. Report E7/57	Confidential	The Effect of Window Apertures on the Mode of Collapse of a Building by Atomic Blast. Miles and Rowe.
6	1957 Tripartite Conf. A.W.R.E. Report E4/57	Confidential	The Effects of Shielding a Building from Atomic Blast by another of the same Size and Shape.
7	1957 Tripartite Conf. A.W.R.E. Report E4/56	Official Use Only	An Investigation of the Effect of Edge Fixation on the Static Strength of Reinforced Concrete Panels. Wood.
8	A.W.R.E. Report E3/56	Confidential	Comparison of the Static Load/Deflection Characteristics of 1/10, 1/4 and 1/2 Scale Models of Reinforced Concrete Panels. Leys.
9	A.W.R.E. Report T45/57	Confidential	Operation Buffalo : Target Response Tests. The Effect on 1/10th Scale Storage Tank Roof Panels.
10	A.W.R.E. Report T44/57	Confidential	Operation Buffalo : Target Response Tests. The Effect on 1/10th Scale Surface Shelters.

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No.	Originator and Reference	Security Classification	Title
51	Nature, Vol.182, No.4645, 8th November, 1958. p.1267	Unclassified	Typhoon Effects of Jaluit Atoll in the Marshall Islands, January 7th, 1958. Article by Dr. Blumenstock of U.S. Weather Bureau.
52	J. Acoustical Society of America, Vol.31, No. 3 March, 1959. p.319	Unclassified	The Propagation of Waves in Slightly Rough Ducts (Acoustical and Electro-Magnetic). T.C. Samuels.
53	A.F.S.W.P. Report ITR-1451	Official Use Only	Operation Plumbbob, Project 30.4, Blast Effects on Protective Vaults.
54	U.S. Army Corps of Engineers, Manuals EM.1110 -345-413, 414, 421.		Blast Damage to Buildings. Amman and Whitney.
55	Armour Research Foundation, Project M069, Report No. 18 (Final Test Report No.1, T.I.L. Ref. P.72265.	Confidential	Effect of Long Versus Short Duration Blast Loadings on Structures.
56	Armour Research Foundation, Project M069, Report No.22 (Final Test Report No. 2) November, 1955, T.I.L. Ref. P.72266.	Confidential	Shielding of Three-Dimensional Blocks.
57	Armour Research Foundation, Project M069, Report No.24 (Final Test Report No. 3) December, 1955, T.I.L. Ref. P.72267.	Confidential	The Effects of Surface Roughness.

No.	Originator and Reference	Security Classification	Title
58	Armour Research Foundation Project M069, Report No. 26 (Final Test Report No. 4), January, 1956, T.I.L. Ref. P.72268.	Confidential	Experimental Observations of Regular Reflection Loadings on Three-Dimensional Blocks.
59	Armour Research Foundation, Project M069, Report No. 29 (Final Test Report No. 6 (March, 1956, T.I.L. Ref. P.72269.	Confidential	Blast Effects of Buildings and Structures : Multi-Storey Structures in the Regular Reflection Region.
60	Armour Research Foundation, Project M069, (Final Test Report No.7), T.I.L. Ref. P.72270.	Confidential	Experimental Observations of Interior Pressures in Hollow Models.
61	Armour Research Foundation, Project M069, Report No. 38, (Final Test Report No.8), T.I.L. Ref. P.73371.	Confidential	The Effect of Wall Panel Failure on Shock Parameters. T.A. Zahner.
62	A.F.S.W.P. ITR-1447.	Official Use only	Operation Plumbbob. Project 33.5. The Internal Environment of Underground Structures subjected to Nuclear Blast. I - The appearance of Dust.
63	A.F.S.W.P. Report ITR-1448	Official Use only	Operation Plumbbob. Project 30.1. Field Test of Reinforced Concrete Dome Shelters and Prototype Door.
64	A.F.S.W.P. Report ITR-1449	Official Use only	Operation Plumbbob. Project 30.2. Response of Dual-purpose Reinforced Concrete Mass Shelter.

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No.	Originator and Reference	Security Classification	Title
35	U.S./A.F.S.W.P. PAPER 22 for 1954 Tripartite Conference on the Capabilities of Atomic Weapons.	Unclassified	Deals with the Estimation of Structural Damage.
36	Princeton University Department of Physics, Report II-6-1950.	Unclassified	Two-Dimensional Shock Tube Studies of a House with a Ridged Roof.
37	Princeton University, Department of Physics, Technical Report II-3-1950.	Unclassified	Shock Tube Studies using Two Similar Rectangular Blocks at Different Separations.
38	Stanford Research Institute, Contract DA-04-167, Eng-379, 1952.	Unclassified	Final Report on the Surface Structure Programme. Underground Tests at Dugway. Vaile, K.B.
39	Symposium on Earthquake and Blast Effects on Structures, Engineering Research Institute, California, 1952.	Unclassified	Computation of Dynamic Structural Response in the Range Approaching Failure. Newmark, N.M.
40	Bulletin of the Seismological Society of America, Vol.43, pp. 7-16, 1953.	Unclassified	A Dynamic Test of a Four-Storey Reinforced Concrete Building. Alford and Housner.
41	Proceedings of the Symposium of Earthquake and Blast Effects of Structures, University of California, June, 1952.	Unclassified	Dynamic Behaviour of Simplified Structures up to the Point of Collapse. Jacobsen, L. K.

No.	Originator and Reference	Security Classification	Title
42	Lehigh University, Final Report, Vol. 3, 1949.	Confidential/ Discreet	Bomb Damage Analysis.
43	Proceedings of the Symposium on Earthquake and Blast Effects on Structures, University of California, June 1952.	Unclassified	Earthquake and Blast Effects on Structures.
44	McGraw Hill, 1932.	Unclassified	Earthquake Damage and Earthquake Insurance. Freeman (Book).
45	Bulletin of Seismological Society of America, Vol.21, pp.277-283, 1931.	Unclassified	Modified Mercalli Intensity Scale, 1931. Wood and Neumann.
46	Bulletin of Seismological Society of America, Vol.32, pp.163-191, 1942.	Unclassified	Earthquake Magnitude, Intensity, Energy and Acceleration. Gutenberg and Richter.
47	Institute of Hydraulic Research, State of Iowa, O.N.R.N.8 onr-500, 1951.	Unclassified	Wind Tunnel Studies with Pressure Distribution of Elementary Building Forms. Chien, Feng, Wang, Siao.
48	T.M.B. Report 940, June, 1955	Unclassified	Collapse Pressures of Metal Panels and Plates. Greenspon, J.E.
49	Journal of Applied Mechanics, Vol.19, p.543, 1952.	Unclassified	Application of the Semi-Graphical Method of Analysis to a Wide Range of Problems. Jacobsen, L.S.
50	A.F.S.W.P. Report ITR-1427	Official Use Only	Operation Plumbbob, Project 3.8, Soil Survey and Backfill Control in Frenchman Flat.

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No.	Originator and Reference	Security Classification	Title
21	C.E.T.G. Preliminary Report ITR-1408, (M.O.D. Ref. No. 378)	Confidential	Operation Plumbbob, Project 1.8B, Effects of Rough Terrain on Drag Sensitive Targets.
22	Bulletin of the Seismological Society of America, Vol. 39, pp.47-56, 1949.	Unclassified	Analysis of Strong Motion Earthquake Records with the Electric Analogue Computer. Housner and McCann.
23	Bulletin of the Seismological Society of America, Vol. 44, pp.513-527, July, 1954	Unclassified	Measured Response of a Structure to an Explosive-Generated Ground Shock. Hudson, Alford and Housner.
24	Trans. of the American Society of Civil Engineers, Vol.121, 1956, Paper No. 2786 (Also as University of Illinois Bulletin, Vol.53, No.73, June, 1956. Engineering Experiment Station Reprint Series No. 56).	Unclassified	An Engineering Approach to Blast Resistant Design. Newmark, N.M. (Basis of F.C.D.A. Tech. Report TR-5-1 of January, 1958).
25	F.C.D.A. Tech. Report TR-5-1, January, 1958 (DGAW/475/58).	Unclassified	Recommended F.C.D.A. Specifications for Blast Resistant Structural Design (Method A).
26	Symposium on Earthquake and Blast Effects on Structures, Los Angeles, June, 1952.	Unclassified	Vibrations of Structures. F.P. Ulrich and D. S. Carder.

No.	Originator and Reference	Security Classification	Title
27	Trans.American Soc. Civil Eng. Vol.107, 1942, p.251	Unclassified	The Plastic Theory of Reinforced Concrete Design. C.S. Whitney.
28	McGraw Hill, New York, 1940.	Unclassified	The Theory of Plates and Shells. S. Timoshenko (Book).
29	J. Amer. Concrete Inst., Vol.26, p.589.	Unclassified	Paper giving the Application of Whitney's Plastic Theory to Panels. Whitney, C.S., B.G. Anderson and E. Cohen.
30	M.I.T. Conference on "Building in the Atomic Age", June, 1952	Unclassified	Steel Frames for Industrial Buildings. Johnston, B.G.
31	Proceedings of the Symposium of Earthquake and Blast Effects on Structures, University of California, June, 1952.	Unclassified	Structural Steel Members and Frames. Johnston, B.C.
32	Bulletin of the National Research Council, No. 90 1933.	Unclassified	Physics of the Earth, Part VI, Seismology.
33	U.S. Bureau of Mines, Bulletin 442, 1942.	Unclassified	Rules of Determining Structural Damage by Earthquakes. Thoenen and Windes.
34	Mine and Quarry Engineering, April, 1953.	Unclassified	Damage to Structures by Ground Vibrations due to Blasting. Morris and Westwater.

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No.	Originator and Reference	Security Classification	Title
7	Armour Res. Foundn. Proj. 90-1052J. Final Report Ref. AD.11942 (M.O.D. Ref. No. 143)	Secret/ Discreet	Planning Programme for Air Force Structures Tests, Parts 1 and 2 - Blast Loading on Cylinders. Part 3, Blast Loading on Cones. (Plans for Trial against Storage Tanks)
8	C.E.T.G. Operation Teapot Project 31.4, Interim Report. CD.9895	Unclassified	Comparison of Responses of Structural Slabs to Static and Atomic Blast Loadings.
9	A.F.S.W.P. -805 August, 1954 (M.O.D. Ref. No. 312)	Confidential	Blast Pressure Requirements for Structural Damage. Newmark. (University of Illinois).
10	C.E.T.G. Preliminary Rpt. Operation Teapot, Proj. 31.1. ITR.1194 and CD.8215	Unclassified	Damage to Conventional and Special Types of Residences exposed to Nuclear Effects.
11	C.E.T.G. Operation Teapot, Project 31.2, Report ITR.1189 M.O.D. Ref. No. 324	Official Use Only	Damage to Commercial and Industrial Buildings exposed to Nuclear Effects. 1955.
12	F.C.D.A./A.E.C. Press Hand-out, 1957	Unclassified	Operation Plumb-Bob. Shelters and Associated Tests at the Nevada Test Site, Spring, Summer, 1957. Prelim. Report of a Continuing Programme by the FCDA/AEC.
13	A.F.S.W.P. 1957 Tripartite Conf. Paper No. 9	Atomic	Blast Loading of Structures and Target Response. Anderson.

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No.	Originator and Reference	Security Classification	Title
14	Proc. Amm. Soc. Civil Engineers, Engineering Mechanics Division, May, 1955.	Unclassified	Blast Resistant Building Frames.
15	Operation Teapot Project 35.5 ITR.1191 CD.9893. Final Report WT-1191 also available.	Unclassified	The Effects of a Nuclear Explosion on Records and Record Storage Equipment (Safes, Filing Cabinets, etc.).
16	Federal Civil Defence Administration Report WT-801 (deleted). (M.O.D. Ref. No. 72)	Confidential/ Atomic	Operation Upshot/Knothole, Project 21.1. Effects of an Atomic Explosion on Underground and Basement Types of Home Shelters.
17	Armour Research Foundation Report M024, M.O.D. Ref. Nos. 107, 117 and 118.	Unclassified	Study of the Vulnerability of an Oil Refinery to Air Blast. Summary Report and Vols. 1 and 2.
18	Armour Research Foundation (M.O.D. Ref. No. 147)	Confidential/ Atomic	Operation Greenhouse, Scientific Director's Report, Interim Report Annexe 3.3, Air Force Sturctures Test Vol.2 - Construction Plans, and Appendix E, Vol.1 - General Blast Loading and Response.
19	A.F.S.W.P. Report ITR-1129 (M.O.D. Ref. No. 247) May, 1955.	Secret/Atomic	Operation Teapot, Project 3.7, Preliminary Report. Effects of Positive Phased Length of Blast on Drag Type Industrial Buildings (Description of Test Buildings and Predicted and Measured Pressures and Loadings).
20	University of Illinois Report AFSWP-494. 21st August, 1953. (M.O.D. Ref. No. 311)	Unclassified	Effect of Long Positive Phased Blast Waves on Drag and Defrection Type Targets. N.M. Newmark.

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DAMAGE TO STRUCTURES ON LAND : Damage by Combined Effects

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T6/57	Confidential	Operation Buffalo: Target Response, Structures Group.
2	Home Office, S.A. Branch (CD/SA.31)	Secret	The Standard of Protection of Trench Shelters.
3	M. of Supply H.E.R. A28/52	Secret	Penetration of Gamma Radiation through the Walls of a Slit Trench.
4	Tri. Con Weapons Effects 1957 Paper AWEC/P(57)55	Secret/Atomic	The Vulnerability of Airfield Runways to Nuclear Explosions. J. E. Henderson.
5	Home Office Report CD/SA48	Confidential	The Safety-Cost Relationship for Certain Types of Surface and Trench Shelters.
6	A.R.D.E. Memo. (B)34/59 July, 1959	Confidential	On the Use of Mathematical Models to Describe the Lethality of Atomic Weapons Against Ground Targets. J. W. Gibson.
7	Air Ministry Science 2. Memo 237 (1954)	Secret	The Power of Bomb Required for the Attack of Airfields.

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No.	Originator and Reference	Security Classification	Title
1	U.S.A. Armour Research Foundation, Illinois Inst. of Technology Report. CD.9275	Unclassified	A Simple Method of Evaluating Blast Effects on Buildings. Revised 1954.
2	Harvard University, Air Cleaning Lab. Report NYO.1595	Unclassified	Blast Damage to Air Cleaning Devices. Progress Report July, 1953, to June, 1955. Billings, Dennis and Silverman.
3	Ammann & Whitney. Report to Chief of Engineers, U.S. Army DA-49-129-Eng-120, Vols 1 and 2. TIL Nos. P.57300 and 57301	Confidential	Design of Structures to Resist Atomic Blast. (Fully Detailed.)
4	American Machine and Foundry Co. Final Rept. Project MR.1013, Vol.I TIL P.65454 Vol.II TIL P.65455	Secret/Discreet Unclassified	Transient Drag and its Effects on Structures. Final Report and Bibliography (Fully Detailed).
5	Bulletin of the American Meteorological Soc. Vol.35, p.95, 1954.	Unclassified	Plate Glass, etc., Breakage. Cox, Plagge and Reed.
6	C.E.T.G. Report ITR.1128 Operation Teapot, Proj. 3.6, 1955 (M.O.D. Ref. No. 307A)	Confidential/ Atomic	Evaluation of Earth Cover as Protection to Above-Ground Structures.

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No.	Originator and Reference	Security Classification	Title
1	Federal Civil Defence Administration, 1955	Unclassified	Programme for Operation Cue. Blast Thermal and Gamma Effects on Buildings and Equipment. The U.S. Civil Defence Atomic Test Programme, Spring, 1955, Nevada.
2	Department of the Army Manual PAM-39-1, March, 1955. (M.O.D. Reference No. 172).	Unclassified	The Tactical Use of Atomic Weapons - Unclassified Military Effects.
3	A.F.S.W.P. Report ITR-1450	Official Use Only	Operation Plumbbob, Project 30.3. Evaluation of F.C.D.A. Family Shelter Mark 1 for Protection against Nuclear Weapons.
4	A.F.S.W.P. Report WT-1175	Official Use Only	Operation Teapot, Project 35.4A, Effects of a Nuclear Explosion on a Typical Liquified Petroleum Gas (L.P. Gas). Installations and Facilities.
5	A.F.S.W.P. Report WT-1181	Official Use Only	Operation Teapot, Projects 36.1 and 36.2. Exposure of Mobile Homes and Emergency Vehicles to Nuclear Explosions.
6	A.F.S.W.P. Report WT-1184	Official Use Only	Operation Teapot, Project 30.4. Nuclear Effects on Machine Tools.
7	A.F.S.W.P. Report WT-1189	Official Use Only	Operation Teapot, Project 31.2. Damage to Commercial and Industrial Buildings Exposed to Nuclear Effects.
8	A.F.S.W.P. Report WT-1218	Official Use Only	Operation Teapot, Project 34.1 and 34.3. Evaluation of Various Types of Personnel Shelters Exposed to an Atomic Explosion.
9	U.S. Federal Civil Defence Administration Manual TM-8-1	Unclassified	Civil Defence Urban Analyses.

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No.	Originator and Reference	Security Classification	Title
10	U.S. Federal Civil Defence Administration, 1953	Unclassified	Report on Operation Doorstep.
11	Federal Civil Defence Administration Report WT-801		Effects of Atomic Explosions on Home Shelters (Includes Displacement, etc. of Models).
12	U.S. Federal Civil Defence Administration Manual TM-5-5	Unclassified	Home Shelters.

Miscellaneous Reports PERSONNEL, ANIMALS, AND VEGETATION: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
8	British Institute of Radiology, 1955. British Journal of Radiology, Supplement No. 6.	Unclassified	Recommendations of the International Commission of Radiological Protection. Revised 1st December, 1954.
9	A/Conf. 15/P/991	Confidential	2nd U.N. Conference. Radiosensitivity of Various Tissues and its Modification by Biological Radio-protective Substances. Hagen and Ernst.
10	A/Conf. 15/P/994 June 1958	Confidential	2nd U.N. Conference. Early Biochemical Reactions Following X-Irradiation. Maas and Schubert.
11	A/Conf. 15/P/2080	Confidential	2nd U.N. Conference. Tissue and Cellular Reactions to the Effect of Ionizing Radiation. Grayevshy.
12	DSI Translation No. 155 May 1956	Unclassified	Protection from X-Rays and Gamma Radiation. Bibergal and Margulis. (USSR).

Miscellaneous Reports TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Nuclear Radiation and Contamination Measurements
Radiac Equipments

No.	Originator and Reference	Security Classification	Title
1	Canadian D.R. Chem. Labs. Report 261, May, 1958. TIL Ref. P.72383	Unclassified	A Recording Ionization Chamber Instrument.
2	At.En.Canada, Ltd. Report AECL-629. TIL Ref.P.72566	Unclassified	Canadian Experience in the Measurement and Control of Radiation Hazards in Uranium Mines and Mills.
3	At.En.Canada, Ltd. Report AECL-594. TIL Ref.P.72555	Unclassified	Health and Safety in Canadian Operations.
4	R.C.A.F. Central Exptl. & Proving Estab. Report 1295 Nov. 1957.	Confidential	C.F.100 Aircraft, Fitment on Air Filters.
5	Canadian DRCL Report 262 Feb. 1958.	Unclassified	A Simple Position of Burst and Yield Indicator. Carruthers et al.

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No.	Originator and Reference	Security Classification	Title
43	D.S.I.R. Water Pollution Res. Lab. Report No. 9 Dec. 1955	Secret	Development of a Field Test for the Estimation of Barium-140 in Natural Waters.
44	A.W.R.E. Report O-28/56	Official Use Only	A Film-Phosphor Dosimeter
45	AERE Report EL/R 1046 Nov. 1952	Unclassified	The Emergency Monitoring of Water Contaminated with Fission Products.
46	A.W.R.E. Report T9/55	Secret	Operation Totem. Radiation Surveys of the Totem Craters.
47	A.W.R.E. Report T7/54	Secret	Operation Totem. Radioactivity Sampling - Deposited Activity.
48	A.W.R.E. Report T49/54	Restricted	Measurement of Beta Radiation on Operation Totem.
49	A.W.R.E. Report T50/54	Restricted	Radiac Dosimeters Tested Under Field Conditions During Operation Totem.
50	ARL/R1/R255 Oct. 1951	Confidential	The Radiac Isotope Rule.
51	A.W.R.E. Report T40/58	Secret	Operation.Antler. Aerial Survey of Radioactivity Deposited on the Ground.
52	A.W.R.E. Report T24/58	Confidential	Operation Antler. Airborne Sampling of Radioactivity.
53	A.W.R.E. Health Physics Div. Memo. HP4/59	Unclassified	Personnel Monitoring Films - Variation of Gamma with Developer Strength. Rowbury.

U.K. Reports TARGET RESPONSE INSTRUMENTATION FOR TRIALS. Nuclear Radiation and Contamination Measurements. Radiac Equipments.

No.	Originator and Reference	Security Classification	Title
54	War Office Joint School of Nuclear Defence Memo. 2/59	Confidential	Radiological Survey from the Air. Lt. Col. A.W. Lister
55	AERE Report EL/R2598 May 1958	Unclassified	The Interpretation of Gamma Ray Scintillation Spectra from Fission Product Mixtures. D. H. Peirson
56	A.W.R.E. Report T113/54	Secret	Operation Hurricane Group Reports Part 52. The Results of Aerial Radiological Survey Over the Australian Coast Line Between Onslow and Broome.
57	A.W.R.E. Report T89/54	Secret	Operation Hurricane Group Reports Part 51. Measurement of the Radioactivity of an Airborne Sample of the Cloud Collected at Broome, Western Australia.

U.K. Reports TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Nuclear Radiation and Contamination Measurements. Radiac Equipments.

No.	Originator and Reference	Security Classification	Title
24	A.W.R.E. Report T39/57	Confidential	Operation Buffalo. The Gamma Flash Spectrometer.
25	A.W.R.E. Report T6/58	Confidential	Operation Antler. The Use of Radiac Survey Meters Nos. 2 & 3 in Aerial Surveys of Radioactive Areas.
26	A.W.R.E. Report T40/58 Dec. 1958.	Secret	Operation Antler. Aerial Survey of Radioactivity Deposited on the Ground. Cater.
27	A.W.R.E. Report T43/58 Nov. 1958.	Secret/Atomic U.K. Eyes Only	Operation Antler. The Remote Measurement of the Variation with Time of Gamma Dose Rate from Fallout.
28	A.W.R.E. Report T50/58 Feb. 1959.	Official Use Only	Operation Antler, Target Response Group. The Recording Techniques Used in the Study of the Electro-magnetic Effects on Ground Radar Equipment. McLeod.
29	A.W.R.E. Branch Memo HP 5/58	Official Use Only	The Calibration of Personnel Monitoring Film Emulsion with Natural Uranium. Rowbury.
30	Admiralty Research Lab. ARL/R1/R866 July, 1958.	Secret U.K. Eyes Only	Naval Radiological Measurements on Operation Grapple. The Energy of the Flash Gamma Radiation. Allwood.
31	A.E.R.E. Report EL/R 2590 (1958)	Unclassified	The Phosphate Glass Dosimeters. D. H. Peirson.
32	Admiralty Paper DPR/BWS/145/58	Unclassified	Radiological Units for Radiac Instruments with Special Reference to Beta Sensitive Instruments. B.W. Soole.
33	LC.153/3345/1 Nov. 1958.	Restricted	The Water-tightness of Quartz Fibre Dosimeters. Neighbour.

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No.	Originator and Reference	Security Classification	Title
34	13th Trip Conf. Tox. Warfare Paper TCR4/58	Official Use Only	A Remote Reading Dose Rate Meter. Perry.
35	12th Tri. Conf. on Tox. Warfare Paper TCR2/57	Confidential	On the Need for Neutron Dosimetry. K. Stewart.
36	Res. & Dev. Branch U.K.A.E.A. Risley Report IGRL-IB/R26 (1957)	Unclassified	Information Bibliography. Health Physics Monitoring Instruments and Methods.
37	A.W.R.E. Report T27/57	Confidential	Operation Buffalo. Air Sampling in the Village and Airfield Area.
38	12th Tri. Conf. on Tox. Warfare Paper TCR9/57	Official Use Only	Aerial Survey Instrumentation. G.C. Dale
39	ARL/N1/C748 Oct. 1957	Unclassified	Underwater Gamma Probe: Possible Use for Monitoring Contamination Entering Condenser and Other Inlets D.M.C. Thomas
40	A.W.R.E. Report T1/57	Official Use Only	Operation Buffalo. The Construction and Operation of a Field Radiological Decontamination Centre.
41	ARL/R1/R865 Jan. 1957	Secret/Atomic/ Guard	Naval Radiological Measurements on Operation Buffalo. Preliminary Report. Lavender and Williams.
42	A.W.R.E. Report T2/57	Official Use Only	Operation Buffalo. Field Trials of Radiac Instruments in a Radioactively Contaminated Area.

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No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T13/57	Confidential	Operation Buffalo: Target Response, Radiac Users Trials.
2	A.W.R.E. TC/3/55	Secret	Tripartite Conference, November, 1955. A Survey of the Sampling Methods used in U.K. Weapon Tests with some Results and Comments.
3	A.W.R.E. T21/54	O.U.O.	Part 14. Multi-directional Gamma Radiation Collimator.
4	A.W.R.E. T22/54	Confidential	Part 15. Multi-directional Gamma Radiation Collimator.
5	A.W.R.E. T23/54	Secret	Part 16. Directional Measurements of Gamma Radiation.
6	A.W.R.E. T5/54	Secret/Atomic	Fission Products Sampling, Parts I and II.
7	Tripartite Conference (9th) Porton (DRB.54/10275)	Restricted	Item 7. Radiological Defence. Aerial Survey of Fallout.
8	Tripartite Conference (9th) Porton (DRB.54/10124)	Secret	Item 7. Radiological Defence. Importance of Radiation Gap.
9	Tripartite Conference (9th) Porton (DRB.54/10276)	Secret	Item 4. Radiological Defence. Monitoring Procedure.
10	Tripartite Conference (9th) Porton (DRB.54/10277)	Confidential	Item 3. Radiological Defence. U.K. Requirements for Radiac and Protective Clothing.
11	A.E.R.E. Report EL/R1798	Secret (limited distribution)	10th Tripartite Conference on Toxicological Warfare. A Report on the Meetings on Radiological Defence. Taylor.
12	A. E.R.E. Report H/P M110	Unclassified	Air Sampling with the Annular Impactor. Stevens.

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No.	Originator and Reference	Security Classification	Title
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14	A.W.R.E. Report T93/54	O.U.O.	Air and Ground Shock Instrumentation for Montebello, 1952 (notes effect of radiation on photographic film).
15	A.W.R.E. Report O-36/56	Official Use Only	The Measurement of Beta Dose using Film Emulsions.
16	A.W.R.E. Report O-30/56	Official Use Only	Air Survey Equipment Type 1398A.
17	"Atomics", Vol. 6, No. 10, October, 1955	Unclassified	Radiological Defence Instruments (Design Requirements).
18	"Nuclear Engineering", May, 1957, p.190	Unclassified	Radiation Detectors - a Survey. Sharpe.
19	A.E.R.E. Report EL/R1798 M.O.D. Ref. No. 180	Secret	10th Tripartite Conference on Toxicological Warfare (1955)
20	A.E.R.E. Report EL/R2118 M.O.D. Ref. No. 281	Secret	11th Tripartite Conference on Toxicological Warfare. A Report on the Meetings on Radiological Defence (1956) including also Thermal Burn and Flash Blindness Data.
21	A.W.R.E. Report TCR-25/57 September, 1957. M.O.D. Ref. No. 390	Secret U.K. Eyes Only	12th Tripartite Conference on Toxicological Warfare. A Report on the meeting on Radiological Defence.
22	A.W.R.E. Report TC10/55	Confidential	A Multi-Channel Gamma Flux Telemetry System. Developed for Operation Hurricane.
23	A.W.R.E. Report T26/57	Confidential	Operation Buffalo. Measurements with Phosphate Glass and Quartz Fibre Dosimeters in the Field.

U.S. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS. Nuclear Radiation and Contamination Measures. Radiac Equipments.

No.	Originator and Reference	Security Classifications	Title
63	A.F.S.W.P. Report ITR-1465	O.U.O./Discreet	Operational Plumbbob. Project 32.4. Fall-out Studies and Assessment of Radiological Phenomena.
64	A.F.S.W.P. Report ITR-1480	O.U.O./Discreet	Operation Plumbbob. Project 35.4. Evaluation of Civil Defense Radiological Instruments.
65	A.F.S.W.P. Report WT-1164	O.U.O./Discreet	Operation Teapot. Project 38.1. Civil Defense Monitoring Techniques.
66	A.F.S.W.P. Report WT-1165	O.U.O./Discreet	Operation Teapot. Project 38.2. Indoctrination and Training of Radiological Defense Personnel.
67	A.F.S.W.P. Report WT-1178A	O.U.O./Discreet	Operation Teapot. Project 37.2. Beta Skin Dose Measurement by Special Design Film-Pack Dosimeters.
68	A.F.S.W.P. Report WT-1182	O.U.O./Discreet	Operation Teapot. Project 30.2. For Utilisation of Telemetering Techniques in Evaluating Residual Radioactive Contamination.
69	A.F.S.W.P. Report WT-1183	O.U.O./Discreet	Operation Teapot. Project 38.5. Off-site Radiological Defense Training Exercises.
70	A.F.S.W.P. Report WT-1186	O.U.O./Discreet	Operation Teapot. Project 30.1. Measurement of Off-site Fall-out
71	A.F.S.W.P. Report WT-1190	O.U.O./Discreet	Operation Teapot. Project 38.3. Evaluation of Civil Defense Radiological Defense Instruments.
72	A.E.C.U.-3666 Feb. 1958	Unclassified	Efficiency of Scavenging Devices Used in Determining Fallout. Report No. 7 (Final) Rosinski.
73	U.S.N./R.D.L. Report TR-244 July, 1958.	Unclassified	Depth-Dosimetry by Means of a Gel-Incorporated Chemical System. Pestaner and Gevantman.

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No.	Originator and Reference	Security Classification	Title
74	USN/RDL Report TR-115	Unclassified	A Wide Range, Gamma Sensitive, Liquid Flow Monitor K.F. Sinclair
75	U.S. Nat. Bureau of Standards Handbook 51 April 1952	Unclassified	Radiological Monitoring Methods and Instruments
76	U.S.N./R.D.L. Report TR-164 May 1957	Unclassified	Interim Report on a Fast - and Slow - Neutron Survey Meter. A.H. Redmond, et al.
77	USN/RDL Report TR-159 May 1957	Unclassified	A Nomogram for Radioactivity in Gross Fission Product Analysis. Rowell and Freiling
78	USN/RDL Report TR-154 May 1957	Unclassified	A Time Arrival Device K.F. Sinclair
79	U.S.N./R.D.L. Report TR-178 May 1957	Unclassified	A Field Beta-Gamma Dose-Rate Meter. F.A. Devlin.
80	10th Tri. Conf. on Tox. Warfare Paper 10-TRI-123	Secret	Helicopter to Ground Radiological Surveying.
81	Los Alamos Scientific Lab. Report LA-2174 May 1958	Unclassified	Experimental Determination of Fast and Thermal Neutron Tissue Dose. Sayeg and Harris

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No.	Originator and Reference	Security Classification	Title
49	U.S.N./R.L. Report No.4746 28th June, 1956, (M. of D. Ref. No. 243)	Unclassified	Techniques for using Fissionable Deposits in Neutron Measurements. Useful for fast Neutron Doses Greater than 10^{10} Neutrons cm^2 Also usable for Radio Assay of 5 f Rare Earth Elements.
50	Civil Effects Test Group Report ITR-1170 May 1955 (M. of D. Ref. No. 246)	Confidential/ Atomic	Operation Tea-pot. Project 39.5 Preliminary Report. Measurement and Permanent Recording of Fast Neutrons by Effects on Semi-Conductors.
51	U.S.N./R.D.L. Report 383 (M. of D. Ref. No. 293)	Unclassified	Beta-contact Hazards associated with Gamma Radiation Measurements of
52	Chem. Warfare Labs. Army Chem. Centre, Md. Paper C.88 Aug. 1956. (M. of D. Ref. No. 305)	Confidential/ Discreet	11th Tripartite Conference on Toxicological Warfare. U.S. Progress Report on Radiological Defence. 1st July, 1955 to 30th June, 1956.
53	Chem. Corps Field Reqs. Agency, Fort McClelland, Ala. Report 345 (M. of D. Ref. No. 306)	Secret/ Discreet	11th Tripartite Conference on Toxicological Warfare. U.S. Progress Report on Service Aspects (U) July, 1955
54	Chem. Corps Field Reqs. Agency, Fort McClelland. Ala. Report C.95 Aug. 1956 (M. of D. No. 307)	Confidential/ Discreet	11th Tripartite Conference on Toxicological Warfare. Staff Study. Problems resulting from Radiological Fallout. Volume I.
55	H.Q., A.R.D.C. Baltimore Md. Paper S.236 July, 1956. (M. of D. Ref. No.308)	Secret/ Discreet	11th Tripartite Conference on Toxicological Warfare. Impact of Fall-out on Air Force Operations. Volume 2 of Problems Resulting from Radiological Fall-out.

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No.	Originator and Reference	Security Classification	Title
56	Victoreen Instrument Co. Report CWL.760-578 30th Nov. 1956 (M.O.D. No. 313)	Unclassified	Research and Development of Photo-conductive test rate Indicator for Ionizing radiation. Final Progress Report to U.S. Army Signal Corps Engineering Labs.
57	Victoreen Instrument Co. Report CWL.760-578 Bibliography Nov. 1956. (M. of D. Ref. No. 314)	Unclassified	Bibliography of Photo-Conductivity for X and Gamma Ray Detection.
58	A.E.C. Health and Safety Lab. N.Y. Operations Office. Report NYO-4859 15th April, 1957 (M. of D. Ref. No. 337)		Method of Calculating Infinity Gamma Dose from Beta Measurement on Gummed Films.
59	U.S.N./R.D.L. Report IER.33. 21st Sept.1956 (M. of D. Ref. No. 338)	Confidential/ Discreet	Preliminary Design Critera for a Shipboard Radiac System.
60	U.S.N./R.L. Report No. 5122. April 16th 1958. TIL Ref. P.74247 ACSIL Ref. 58/2738	Unclassified	A Standardised X-Ray Field Range. Provision of Calibrated X-Ray Field of Energy 30-300 Kev.
61	U.S.N.R.D.L. Report TR-158 10th April, 1957 TIL Ref. P.72547 ACSIL Ref. 58/2613	Unclassified	Performance Characteristics of a Aerosol Contamination Chamber and Study of Decontamination Methods.
62	A.F.S.W.P. Report ITR-1464	O.U.O./Discreet	Operation Plumbbob. Project 32.3. Evaluation of Countermeasure Systems Components and Operational Procedures.

U.S. Reports TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Nuclear Radiation and Contamination Measurements. Radiac Equipments

No.	Originator and Reference	Security Classification	Title
37	National Bureau of Standards Report, 1955. (M. of D. Ref. No. 106)	Unclassified	National Bureau of Standards Report on Test of Photographic Field Dosimeter with A.W.R.E. Laboratory Photographic Density Curves for Films PM.1, PM.2, PM.3, PM.4, PM.5, PM.6 and PM.7, covering from 0.1 to 104R, and Field Atomic Tests inter-comparison with an A.E.C. Dosimeter.
38	U.S. Chem. Corps. Chem. & Radiological Labs. Report CRLR-311 21st Dec. 1953. (M. of D. Ref. No. 129)	Confidential/ Discreet	Operation Upshot - Knothole. Project 6.4. Evaluation of Chemical Dosimeters.
39	U.S.N./R.D.L. Report TR-33 Feb. 1955. (M. of D. Ref. No. 137)	Unclassified/ Discreet	A Standard Roentgen Ray Facility.
40	Naval Research Laboratory Report NRL.4575 1st Aug. 1955. (M. of D. 148)	Unclassified/ Discreet	The Neutron Converter. Thermal Neutron Flux Calibration.
41	National Bureau of Standards Report NBS.2902 8th Oct. 1954. (M. of D. Ref. No. 152)	Unclassified	The Dose Received by Partially Shielded Gamma Ray Detectors.
42	Naval Research Lab. Report NRL.4566 22nd July, 1955. (M. of D. Ref. No. 166)	Unclassified	Experimental Gamma Radiac Calibrator.

No.	Originator and Reference	Security Classification	Title
43	CONARC Board No. 2 Proj. No. 1876 15th June, 1955. (M. of D. Ref. No. 176)	Unclassified	Plan of Test - Proj. NR.1876 - Test of a Charger, Radiac Detector - PP.995.
44	Tentative Edition NRL Report 4459 13th Dec. 1954. (M. of D. Ref. No. 181) A.C.S.I.L. Ref. 55/1632	Unclassified	A Shallow-Well Gamma Calibration Range.
45	Naval Medical Research Institude Bethesda A.F.S.W.P. Report UKP-10 (M. of D. Ref. No. 215)	Confidential/ Discreet	Operation Upshot - Knothole. Project 2.2b. Preliminary Report Residual Gamma Depth Dose Measurements in Unit - Density Material (1953)
46	U.S. Naval Research Lab. Report NRL.4706 12th March. 1956. (M. of D. Ref. No. 221)	Unclassified	A Pulsed-Light Reader for the DT-60 Glass Dosimeter.
47	U.S. Naval Ordnance Test Station China Lake California. Report NOTS.1218 (M. of D. Ref. No. 227)	Unclassified	Criteria for Evaluating Gamma Radiation Exposures from Fall-out following Nuclear Detonation. Reprint from Radiology. Volume 66, No. 4 pages 558 to 594. 1956.
48	CONARC Arctic Test Branch Proj. 1861 13th July, 1956, (M. of D. Ref. No. 241)	O.U.O. Discreet (CC)	Testing of Radiac Meters IM-20/UD. (Fountain Pen Type 0-50 R)

U.S. Reports TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Nuclear Radiation and Contamination Measurements. Radiac Equipments

No.	Originator and Reference	Security Classification	Title
19	A.F.S.W.P. Report WT-317 (M.O.D. No. 38)	Secret/Restricted Data	Operation Buster 1951, Project 6.1 b. Evaluation of Dosimetric Meterials.
20	A.F.S.W.P. Report WT-315 (M.O.D. No.39)	Secret/Restricted Data	Operation Buster 1951, Project 4.1. Radiation Dosimetry (Lucite Spheres)
21	U.S./A.E.C. Oak Ridge Lab. Report U.K.P. 49 (M.O.D. No.40)	Confidential	Operation Upshot Knothole. Evaluation of Rapid Aerial Radiological Survey Techniques.
22	U.S./A.E.C. Oak Ridge Lab. Report WT-392 (M.O.D. No.41)	Secret/Restricted Data	Gamma Radiation as a Function of Time with Dropable Telemeters.
23	U.S./A.E.C. Div. of Biology and Medicine. Report WT-796 (M.O.D. No.42)	Confidential	Operation Upshot Knothole. Project 28.1 Tests of a Radiation System (1953).
24	A.F.S.W.P. Report WT-337 (M.O.D. No.43)	Confidential	Operation Jangle. Project 6.1. Evaluation of Military Radiac Equipment (1951).
25	A.F.S.W.P. Report WT-536 (M.O.D. No.44)	Confidential	Operation Snapper. Project 6.7. Evaluation of Air Monitoring Instruments (1952).
26	A.F.S.W.P. Report WT-351 (M.O.D. No.46)	Secret	Operation Jangle, 1951. Project 2.1c. Aerial Survey of Local Contaminated Terrain.
27	A.F.S.W.P. Report UKP.46 (M.O.D. No.50)	Confidential	Operation Upshot Knothole, Project 6.8. Evaluation of Military Radiac Equipment.
28	U.S./A.E.C. Oak Ridge Lab. Report UKP.44 (M.O.D. No.51).	Confidential	Evaluation of Chemical Dosimeters.

U.S. Reports TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Nuclear Radiation and Contamination Measurements. Radiac Equipments

No.	Originator and Reference	Security Classification	Title
29	A.F.S.W.P. Report WT.348 (M.O.D. No.52)	Confidential	Operation Jangle. Gamma-Ray Spectrum Measurements of Residual Radiation.
30	U.S./A.E.C. Oak Ridge Lab. Report WT-318 (M.O.D. No. 53)	Secret	Airborne Radiac Evaluation. AN/ADR -3 and D-1 Radioactive Cloud Tracers.
31	U.S./A.E.C. Oak Ridge Lab. Report WT-507 (M.O.D. No.55)	Secret	Radiation Monitoring Measurements. Electronic Techniques for Gamma/ Time to 15 Minutes.
32	U.S.N./R.D.L. Report WT-3 (M.O.D. No.59)	O.U.O.	Operation Greenhouse. Scientific Director's Report, Annex 5.1 Annex A. Alkali Halide and Phosphate Glass Radiological Casualty Dosimeters (1951).
33	N.Y. Naval Shipyard FCDA Report WT-805.	Confidential/ Restricted Data	Operation Upshot Knothole, Project 22.2. Various Aspects of Nuclear Radiation Measurements for Civil Defence Radiological Purposes (1953).
34	U.C.L.A. Report WT-803 (M.O.D. No.79)	Confidential/ Restricted Data	Operation Upshot Knothole, Project 29.2. Measurement of Fast Neutrons by Effects on Semi-Conductors (1953)
35	U.S./A. E.C. Instrument Branch. Health and Safety Lab. N.Y. Operations Office. Report NYO-4577 (M.O.D. No.84) Aug. 1954.	Unclassified	Mathematical Evaluation of Airborne Radiological Survey Data.
36	U.S.N./R.D.L. Tech. Memo. No.18 17th Nov. 1954. (M. of D. Ref. No.101)	Unclassified/ Discreet	Estimation of the Gamma Dose Associated with Radioactive fall-out Material.

U.S. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Nuclear Radiation and Contamination Measurements. Radiac Equipments.

No.	Originator and Reference	Security Classification	Title
1	Los Alamos Scientific Lab. Report LA 1685 (M. of D. No. 95)	O.U.O. Restricted	Some Observations on Air Sampling Techniques used at the Nevada Proving Ground. 1954
2	Signal Corps Eng. Lab. (U.S.) Evans Sig.Lab.Tech.Memo 1511 (DRB.54/10619)		Decontaminability of Finishes for Radiac Instruments.
3	U.S.A.F. School of Aviat. Medicine (DRB.54/11658)	Unclassified	A Constant Air Monitor for Alpha Emitting Particles.
4	Civil Effects Test Group ITR.1182	Official use only	Operation Teapot, 1955. Project. 30.2 - Locations of Fallout. Telemetry Points, and Details of Max. Recordings at Teapot Series, 1955.
5	U.C.R.L.-4556, August, 1955. TIL P.63250	Unclassified	A Continuous Alpha Air Monitor compensating for the Natural Atmospheric Radioactivity. Sawle.
6	C.E.T.G. ITR.1186	Official use only	Remote and Automatic Gamma Monitors used at Teapot, 1955.
7	U.S. Naval Research Lab. Report 4571 (M. of D. No. 135)	Unclassified	A simple Meter for Radioactive Fallout. Klick, et al.
8	U.S. Naval Res. Lab. Progress Report, June, 1956. TIL P.59200	Unclassified	A Setector of Radioactive Airborne Particles for the Nautilus.
9	U.S. Naval Med. Res.Inst. Bethesda. Res.Report Proj. NM.006-012.04.69, 1954. TIL P.55177	Unclassified	Development Study of Use of Vycor Glass for Gamma Ray Dosimetry.

U.S. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Nuclear Radiation and Contamination Measurements. Radiac Equipments.

No.	Originator and Reference	Security Classification	Title
10	U.S.N. Radiological Def. Lab. Report USN/RDL-420 TIL P.62382	O.U.O. Discreet	Application of the Scintillation Spectrometer to Radioactive Fallout Spectra Analysis.
11	A.F.S.W.P. Report WT-63 (M.O.D. No.17)	Secret/Restricted Data	Operation Greenhouse. Project 6.7 Evaluation of Ground Radiac (May 1951). Signal Corps Engineering Labs.
12	U.S./A.E.C. Oak Ridge Lab. Report UKP-48 (Extract) (M.O.D. No.20)	Confidential	Evaluation of Naval Airborne Radiac Equipment.
13	USN/RDL Report WT-26 (M.O.D. No.21)	Secret/Restricted Data	Operation Greenhouse. Scientific Director's Report Annex 6.5. Interpretation of Survey Meter data (1951).
14	U.S./A.E.C. Oak Ridge Lab. Report WT-15 (M.O.D. No.30)	Secret/Restricted Data	Operation Greenhouse. 1951. Scientified Director's Report, Annex 2.3. Exposure Containers for the Bio-medical Programme.
15	Army Chem. Centre. Report WT-28. (M.O.D. No. 32)	Unclassified.	Operation Greenhouse. Scientific Director's Report 5.1 Annex C Development of the Chemical Corps Dosimeter.
16	U.S./A.E.C. Oak Ridge Lab. Report WT-62. (M.O.D. No.33)	Confidential	Operation Greenhouse. Scientific Director's Report. 5.1 Annex B Polaroid Dosimeter.
17	U.S./A.E.C. Oak Ridge Lab. Report WT-529 (M.O.D.No.36)	Secret/Restricted Data	Gamma Depth Dose Measurement in a unit-Density Material (Lucite).
18	U.S./A.E.C. Oak Ridge Lab. Report WT-555 (M.O.D. No. 37)	Secret/Restricted Data	Summarised Properties of Various Threshold Detectors. Gives Energy Bands for 13 Systems.

U.K. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Thermal Radiation Measurement.

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T70/54	Confidential	Measurement of Total Integrated Heat Output.
2	A.W.R.E. T101/54	Official use only.	The A.M.L. Spectrum Intensity Recorder, Part I.
3	A.W.R.E. T24/54	Confidential	The A.M.L. Spectrum Intensity Recorder, Part II. Interim Report on Records obtained.
4	A.W.R.E. T25/54	Confidential	The A.M.L. Spectrum Intensity Recorder, Part III, Final Results.
5	A.W.R.E. T68/54	Confidential	Thermal Radiation Intensity - Time Distribution by a Photoelectric Method.
6	A.O.R.G. ORG(W. & E.) Report No. 354A.	Top Secret	High Temperature Radiation and Heat Sensitive Papers (Parts I, II and III).
7	A.O.R.G. ORG (W. & E.) Report No. 354.	Restricted	High Temperature Radiation and Heat Sensitive Papers (Part II only).
8	C.D.E.E. Porton, Tech. Paper No. 586.	Restricted	A Telephotometer for Measurement of Atmospheric Transmission.
9	Report AWEC/P(57)315	Confidential	A simple Thermal Radiation Dose Indicator for Field Use.
10	Report AWEC/P(57)316	Restricted	A wide-angle Photo-electric Integrating Flashmeter.
11	A.W.R.E. Report T56/57	Official use only	Atmospheric Transmission Measurements with a Telephotometer.
12	Porton Technical Paper (R)4, July 1957.	Confidential	A Simple Thermal Radiation Dose Indicator for Field Use (Paints). Lane, W.R. and Prewett, W.C.
13	Fire Research Note 363/ 1958.	Unclassified	A Simple Thermal Radiation Dose Meter. Smith, P.G.

U.K. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Thermal Radiation Measurement.

No.	Originator and Reference	Security Classification	Title
14	Fire Research Note 362/1958.	Unclassified	The Theory of a Simple Dose Meter for Thermal Radiation. Thomas P.H.
15	Porton Tech. Paper (R)17 Jan. 1959.	Restricted	Plane Surface Reflections from an Aerial Source of Visible Radiation. Dorman and Wootten.

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TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Thermal Radiation Measurement

No.	Originator and Reference	Security Classification	Title
1	U.S. Univ. of Rochester U.R.353 P.49005	Unclassified	Evaluation of Black Polyethylene as a Skin Simulant under Fabrics exposed to Thermal Radiant Energy.
2	U.S.N.Y. Naval Shipyard Mat.Lab. (P.49785)	Restricted/ Discreet	Requirements of a Laboratory Source to simulate the Thermal Radiation emitted during an Atomic Explosion.
3	U.S. Univ. of Rochester U.R. 387	Unclassified	Shaping Thermal Energy Pulses from a Carbon Arc Source.
4	U.S. Naval Radiological Defence Lab. USN/RDL/ TR-35 (AFSWP-797) TIL P.54038	Unclassified	Measurement of Intense Beams of Thermal Radiation. Broido and Willoughby.
5	Wright Air Dev. Centre Tech. Report 53-210 M.O.D. Ref. 252	Secret/Atomic	Instrumentation for Ground/Air Observations at Operation Ivy.
6	U.S. Naval Radiological Defence Lab. 1957 Tripartite Conference Paper No. 12.	Unclassified	Thermal Radiant Flux Measurement. Plum.
7	A.F.S.W.P. Report T.O.1, 54-8	Unclassified	Thermal Pulse Properties of Five High Intensity Laboratory Sources. (1954).
8	U.S.N.R.D.L. Report WT-3 (M.O.D. Ref. No. 58)	Official use only.	Operation Greenhouse. Design and Operation of High Speed Bolometers, 1951.
9	U.S.N. R.D.L. Report WT-3 (M.O.D. Ref. No. 57)	Official use only.	Operation Greenhouse. The Method of Measurement of Spectral Energy within Two Wave Length Intervals as a Function of Time.

U.S. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Thermal Radiation Measurement.

No.	Originator and Reference	Security Classification	Title
10	University of Rochester Report UR-387, June 1955. (M.O.D. Ref. No. 98)	Unclassified	A Method of Shaping Thermal Energy Pulses from a Carbon Arc Source (Slotted Wheel).
11	Wright Air Development Centre Report W.A.D.C.-52-210. (M.O.D. Ref. 252)	Confidential/ Discreet	Instrumentation for Measurement of Thermal Radiation.
12	A.F.S.W.P. Report WT-1527	Official use only.	Operation Plumbbob. Project 26.3. Temperatures from Underground Detonation, Shot Ranier.
13	A.F.S.W.P. Report WT-1187	Official use only.	Operation Teapot. Project 39.3. Thermal Radiation Measurement.
14	U.S.N./R.D.L. Report TR-236(AFSWP-1078) May, 1958.	Unclassified	Experimental Study of the Effect of Field of View on Transmission Measurements. Gibbons.

U. S. Reports

TARGET RESPONSE INSTUMENTATION FOR TRIALS: Blast Pressure Measurement

No.	Originator and Reference	Security Classification	Title
1	Ballistic Research Labs. 1957 Tripartite Conf. Paper No. 19	Unclassified	Blast Instumentation. Lampson and Meszaros.
2	Ballistic Research Labs. 1957 Tripartite Conf. Paper No. 20	Unclassified	Instrumentation for Measurement of Underwater Shock Waves from Nuclear Underwater Explosions. Hartmann.
3	U.S.N.O.L. NavOrd. Report 3697, May 1954.	Confidential/ Discreet	Equipment for Quantitative Measurements of Underwater Shock Waves from Very Large Explosions. III - Tests on a System Built by the Rutishana Corporation.
4	Joint Task Force 132. Report WT-606. November 1952. (M.O.D. Ref. No. 138)	Confidential/RD.	Operation Ivy. Instrumentation for Blast Measurement by the Sandia Corporation.
5	A.F.S.W.P. Report ITR-1426	Official Use Only	Instrumentation of Structures for Air Blast and Ground Shock Effects.
6	A.F.S.W.P. Report WT-790	Confidential/ Atomic	Operation Upshot Knothole. June 1953. Project 24.3. A.E.C. Shelter Instrumentation - Blast Effects.
7	NRL Report 4722 June, 1956	Unclassified	Magnetic Tape Recording System for Pressure-Time Records of Underwater Explosions. Howard.

U.K. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: Blast Pressure Measurement.

No.	Originator and Reference	Security Classification	Title
1	1957 Tripartite Conference Paper H10/52(X)	Confidential	Shock Waves in Air from Model Scale Charges.
2	A.W.R.E. Report T86/54.	Secret	Measurement of Air Blast.
3	A.W.R.E. Report T9/58	Confidential	Measurement of Blast Pressures Associated with Various Service and Civil Defence Targets.
4	A.W.R.E. Report T1/58	Confidential	Operation Buffalo. Air Shock Measurements on Rounds 1 and 2.
5	A.W.R.E. Report T42/58 Dec. 1958.	Confidential	Operation Antler. Measurement of Ground Shock.
6	A.W.R.E. Report T91/54	Confidential	Montebello Tests 1952. The Mechanical Diaphram Gauge for Recording Air Blast.
7	A.W.R.E. Report T97/54	Confidential	Montebello Tests 1952. The Measurement of Permanent Ground Movement by Survey.
8	A.W.R.E. Report T92/54	Confidential	Montebello Tests 1952. The Measurement of Air-Blast Using Petrol Cans and Toothpaste Tubes
9	A.W.R.E. Report T93/54	Confidential	Montebello Tests 1952. Electronic Apparatus for Recording Air Blast
10	A.W.R.E. Report T90/54	Confidential	Montebello Tests 1952. A Mechanical Multi-Piston Gauge for Recording Air Blast
11	A.W.R.E. Report T96/54	Confidential	Montebello Tests 1952. An Apparatus for Measuring Transient Grount Movement.

U.K. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: General Instrumentation. Measurement of Position, Velocity and Acceleration

No.	Originator and Reference	Security Classification	Title
12	A.W.R.E. 1957 Tripartite Conf. Paper 0-50/56	Official Use Only	The Development of the Kerr Cell Cine Camera, Part. 5. High Speed Rotating Mirrors.
13	A.W.R.E. 1957 Tripartite Conf. Paper 0-11/53	Unclassified	Single and Repetitive Spark Light Sources.
14	A.W.R.E. 1957 Tripartite Conf. Paper 0-17/56 AWEC/P(57)317	Official Use Only.	A 4-Spark Repetitive Light Source using Beam Splitters.
15	A.W.R.E. 1957 Tripartite Conf. Paper T37/57	Secret/Atomic	Operation Buffalo: Measurement of Ground Shock and Crater.
16	I.R./423. D.S.I. Report 101. 7 pp. December 1956.	Secret	Trials of Infra-Red Equipment for the Detection of Guided Weapons.
17	A.W.R.E. Report T68/57	Confidential	Operation Buffalo. Instrumentation Group Acceleration Recorded on Target Response Items.
18	A.W.R.E. Report T69/57	Secret	Operation Buffalo. Instrumentation Group Effects of Models and Idealised Targets.
19	A.W.R.E. Report T32/58	Confidential	Operation Buffalo. Target Response Tests, Instrumentation Group. Part 3 - Special Instrumentation.
20	A.W.R.E. Report T49/58 March 1959	Confidential	Operation Buffalo, Target Response Tests. Instrumentation Group. The Cine-Photography of Target Response Items.
21	A.W.R.E. Report TC11/55	Confidential	Firing Control and Instrument Synchronization

U.K. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: General Instrumentation. Measurement of Position, Velocity and Acceleration.

No.	Originator and Reference	Security Classification	Title
22	A.W.R.E. Report TC12/55	Restricted	The Photography of Nuclear Explosions.
23	A.W.R.E. Report T95/54	Confidential	Montebello Tests 1952. A Photographic Method of Determining the Velocity of the Air Shock.
24	A.W.R.E. Report T94/54	Confidential	Montebello Tests 1952. An Electrical Method of Determining the Velocity of the Air Shock

U.S. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: General Instrumentation. Measurement of Position, Velocity and Acceleration.

No.	Originator and Reference	Security Classification	Title
20	A.F.S.W.P. Report WT-1197	Official Use only.	Operation Teapot. Project 39.4b. Technical Photography, (High Speed Blast Biology),
21	Artillery and Guided Missile School, Fort Still, Oklahoma. June, 1955. Report on Exercise Desert Rock 6.	Confidential	Location of Atomic Bursts by a Field Artillery Observation Battery.
22	Operation Trumpet. 1959.	Secret	Nuclear Surveillance (Letter from Lt.Col. G.B. Donald, 27/8/58).
23	ATSWD-S000.9/ 93(c) U.S. Continental Army Command Sept. 1958.	Confidential	Statement of Qualitative Material Requirements - INBASS. (Indirect Nuclear Burst Assessment and Surveillance System).

U.K. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: General Instrumentation. Measurement of Position, Velocity and Acceleration.

No.	Originator and Reference	Security Classification	Title
1	A.W.R.E. T9/57	Confidential	Operation Buffalo: Target Response, Instrumentation Group.
2	A.W.R.E. TC 2/55	Secret	Tripartite Conference, November, 1955. Abstracts of British Reports on Instrumentation for Full-scale Atomic Weapons Trials.
3	Tripartite Conf. September 1957, Paper 0-26/56 AWRE	Confidential	A Peak Indicator for Ground Shock Measurements.
4	Tripartite Conf. September 1957, Paper T96/54 AWRE	Confidential	Apparatus for measuring Transient Ground Movement.
5	Tripartite Conf. September 1957, Paper 0-52/56 AWRE	Confidential	A Highly-damped Velocity Meter for Ground Shock Measurements.
6	Tripartite Conf. September 1957, Paper 0-34/57 AWRE	Confidential	A Servo-accelerometer for Ground Shock Measurements.
7	Tripartite Conf. September 1957, Paper 0-35/57 AWRE	Confidential	A Moving-iron Velocity Meter for the Measurement of Ground Shock from Atomic Weapons.
8	Tripartite Conf. September 1957, Paper 0-46/56 AWRE	Official Use Only	The Development of the Kerr Cell Ciné Camera. Part 1. The Design and Performance of the Prototype.
9	Tripartite Conf. September 1957, Paper 0-47/56 AWRE	Official Use Only	The Development of the Kerr Cell Ciné Camera. Part 2. The Production Model.
10	Tripartite Conf. September 1957, Paper 0-48/56 AWRE	Official Use Only	The Development of the Kerr Cell Ciné Camera. Part 3. The Electronic Equipment of the Kerr Cell.
11	A.W.R.E. Tripartite Conf. Paper 0-49/56 (1957)	Official Use Only	The Development of the Kerr Cell Ciné Camera. Part 4. Optical Design Considerations.

U.S. Reports TARGET RESPONSE INSTRUMENTATION FOR TRIALS: General Instrumentation. Measurement of Position, Velocity and Acceleration

No.	Originator and Reference	Security Classification	Title
1	Civil Effects Test Group Project 39.4A. CD.9896	Unclassified	Technical Photography at Operation Teapot - Documentary.
2	Civil Effects Test Group Project 39.4C. CD.9897	Unclassified	Technical Photography at Operation Teapot - Physical Phenomena.
3	Civil Effects Test Group Project 39.4B. CD.9898	Unclassified	Technical Photography at Operation Teapot - High Speed.
4	Engineering Res. Assocts. Inc. Report PX.29565, August, 1951. TIL No. P.48039	Official/ Discreet	Instrumentation for Underground Explosion Test Programme. Interim Technical Report No. 1 - Dry Clay.
5	J. for Soc. of Motion Picture and T.V. Engns. Vol. 60, No. 4, p.405, April, 1953	Unclassified	Use of Photography in the Underground Explosion Test Programme, 1951-1952. Blunt. (Dugway Proving Ground).
6	Ballistic Res. Laboratories. 1957 Tripartite Conf. Paper No. 21	Unclassified	Target Response Instumentation. Meszaros.
7	A.F.S.W.P. 1957 Tripartite Conf. Paper No. 22	Unclassified	Nuclear Field Test Instumentation. Connolly.
8	A.F.S.W.P. Report U.K.P.-50, 1953. (M.O.D.Ref.No. 50A)	Secret/R.D.	Operation Upshot Knothole - Project 6.12. Determination of Height of Burst and Ground Zero, Short and Long Range.
9	L.A.S.L. Report A.E.C.U.-2969. (M.O.D. Ref. No. 92)	Unclassified	15 Million Frames per Second Camera.

U.S. Reports. TARGET RESPONSE INSTRUMENTATION FOR TRIALS: General Instrumentation. Measurement of Position, Velocity and Acceleration.

No.	Originator and Reference	Security Classification	Title
10	Report N.R.L. 4668, January 1956. (M.O.D. Ref. No. 194)	Unclassified/ Discreet	Part I. - Instrumentation Tests at Oak Ridge National Laboratory.
11.	A.F.S.W.P. Report ITR.1427.	Official Use only.	Operation Plumbbob. Project 3.8. Soil Survey and Backfill Control in Frenchman Flat.
12.	A.F.S.W.P. Report ITR-1499.	Official Use only.	Operation Plumbbob. Programme 26. Preliminary Summary Report of Strong-Motion Measurements from a Confined Underground Nuclear Detonation.
13.	A.F.S.W.P. Report ITR-1525	Official Use only.	Operation Plumbbob. Project 30.5a. Dome-Structure Response Instrumentation.
14.	A.F.S.W.P. Report ITR-1528	Official Use only.	Operation Plumbbob. Project 26.4A. Surface Motion from an Underground Detonation.
15.	A.F.S.W.P. Report ITR-1529	Official Use only.	Operation Plumbbob. Project 26.4b. Sub-Surface Motion from a Confined Underground Detonation - Part I.
16.	A.F.S.W.P. Report WT-1530	Official Use only.	Operation Plumbbob. Project 26.4. Surface Motions from an Underground Explosion.
17.	A.F.S.W.P. Report WT-1532	Official Use only.	Operation Plumbbob. Project 26.4f. Photographic Analysis of Earth Motion, Shot Ranier.
18.	A.F.S.W.P. Report WT-1107	Official Use only.	Operation Teapot. Project 3.10. Structures Instrumentation.
19.	A.F.S.W.P. Report WT-1169	Official Use only.	Operation Teapot. Project 39.4a. Technical Photography, Documentary.

U.K. Reports. DAMAGE TO MATERIALS: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
44	A.W.R.E. Report O-9/58	Official Use Only	Recommended Reagents for Radialogical Decontamination
45	A.W.R.E. Report T-31/58	Confidential	Operation Buffalo. The Attempted Decontamination of Roofs by Wash-down.
46	A.W.R.E. Report T-35/58	Confidential	Operation Antler. Nautron Induced Activity in Materials Used in Items of Military Equipment. Vol. 1. Text. Vol. 2 Figures.
47	Medical Research Council Report PABE/100 Feb. 1957	Official Use Only	Review of Maximum Permissible Levels of Fallout Contamination for Food and Drinking Water. G. J. Neary.
48	Res. & Dev. Branch U.K.A.E.A. Risley IGRL-IB/R-27 (1957)	Unclassified	Information Bibliography. Radioactive Decontamination Procedures and Equipment.
49	Air Ministry Science 2. Memo 273 (1957)	Secret/Atomic	The Effects of Radioactivity on P.R. Film.
50	ARN/NI/C707 Jan. 1958	Unclassified	Simulants of Radioactive Contamination for Training Decontamination Parties. E.W. Jackson.
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Miscellaneous Reports. DAMAGE TO MATERIALS: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
1	Canada D.R. Board Suffield Tech.Paper 18 Summary (Home Office CD.6181)	Secret	A Study of Mixed Fission Product Contamination on Concrete and Earth Areas.
2	IR/338. DSI. Report (87), 5 pp. February, 1956.	Secret	Describes the Russian Work on the Chemical Effects of Ionising Radiations.

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No.	Originator and Reference	Security Classification	Title
25	R.A.E. Library Bibliography No. 195	Unclassified	List of (Unclassified) References on Atomic, Photon, and Ion Propulsion of Aircraft; the Shielding of Aircraft Nuclear Reactors; the Medical Hazards of Atomic Powered Aircraft; and the Effect of Atomic Radiation on Aircraft Materials and Components.
26	A.W.R.E. Report O-32/56	Official Use Only	Decontamination. Caesium Tellurium and Iodine on Cotton. Stevenson.
27	"Nature", Vol. 179. No. 4565, p.864.	Unclassified	Effects of Nuclear Radiation on Semi-conductors. Gorton.
28	Proc.I.R.E. Vol.45 No. 7, p.931	Unclassified	The Effect of Nuclear Radiation on semi-conductor Devices. Keister and Stewart.
29	1957 Tripartite Conf. Paper AWEC/P(57)211	Secret/Atomic	Neutron Induced Activities in Soil.
30	1957 Tripartite Conf. Paper AWEC/P(57)210	Confidential	An Investigation into Neutron Induced Activities of Food-stuffs and Medical Supplies at Buffalo, Round 1.
31	A.W.R.E. Report T22/57	Confidential	Operation Buffalo, Decontamination Group Report, Parts 1-4.
32	A.W.R.E. Report O-49/55	Official Use Only	A Guide to Radiological Decontamination After a Nuclear Explosion or Radiological Attack.
33	A.W.R.E. Report T4/57	Confidential	Decontamination of Radioactively Contaminated Drinking Water in the Field.
34	Ministry of Supply DAW(Plans) Note 15.	Confidential	Neutron Induced Radioactivity. Garrard and Bassett.

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No.	Originator and Reference	Security Classification	Title
35	12th Tri. Conf. on Tox. Warfare Paper TCR8/57	Official Use Only	The Effect of Induced Activity in Soil on Dose-Rate from Fallout. G. C. Dale.
36	12th Tri. Conf. on Tox. Warfare Paper TCR20/57	Confidential	Decontamination of Personnel and Equipment - Techniques and Equipment. Catherall and Stevenson.
37	A.W.R.E. Report T28/57	Unclassified	Operation Buffalo. Measurement of the Radioactivity of Water Contaminated by Fallout.
38	Porton Tech. Paper R6. May, 1957	Confidential	The Retention of Fission Products by Soils - Preliminary Studies. Neale and Letts.
39	11th Tri. Conf. on Tox. Warfare U.K. Paper 11-TRI-C117 1956	Confidential	Requirements for Decontamination in the Field.
40	AWRE Report 0-22/54	Secret	The Decontamination of Radioactive Clothing Part 1. Laboratory Investigations.
41	AWRE Report 0-23/54	Secret	The Decontamination of Radioactive Clothing Part 2. Laundry Investigations and Recommendations.
42	ARL/N1/C729 Sept. 1956	Confidential	The Retention of Radioactive Contamination by a Fire-Fighting Hose. Jackson.
43	A.W.R.E. Report 0-66/57	Official Use Only	Protective Clothing for Use on Weapon Trials.

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No.	Originator and Reference	Security Classification	Title
1	A.R.D.E. Report (B7/56)	Confidential	The Effect of High Energy X-rays on the Thermal Detonation of Service Lead Azide. Groocock and Phillips.
2	Hurricane Ad. Res. Lab. Report R4/R.862	Secret	Decontamination of Personnel and Equipment.
3	A.W.R.E. 0-23/54	Secret	Decontamination of Clothing II. Laundry Investigations and Recommendations.
4	A.W.R.E. 0-22/54	Secret	Decontamination of Clothing I. Laboratory investigations.
5	A.W.R.E. 0-10/54	Confidential	Use of Vapour Compression Evaporation for Purification of Contaminated Water.
6	Montebello A.R.L. ARL Report R3/0760	Secret	Radiochemical Experimental Decontamination of Naval Construction Materials II. Dry Samples.
7	Home Office, (1949) (CR.2339)	Secret	Protection against Gamma Rays afforded by various thicknesses of Concrete.
8	A.W.R.E. T14/54	O.U.O.	Decontamination of Radioactive Clothing I. Preliminary Survey.
9	A.W.R.E. T15/54	Secret	Decontamination of Radioactive Clothing II. Laboratory Investigations.
10	A.W.R.E. T51/54	Secret	Decontamination of Radioactive Clothing III. Laboratory Investigations and Recommendations.
11	A.W.R.E. T104/54	O.U.O.	Prevention and Removal of Radioactive Contamination.
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U.K. Reports. DAMAGE TO MATERIALS: Nuclear Radiation, Contamination and Decontamination

No.	Originator and Reference	Security Classification	Title
13	A.W.R.E. T106/54	Secret	The Prevention and Removal of Radioactive Contamination Part VI. Decontamination of Aircraft, and Health Control at Woomera and Amberley.
14	A.W.R.E. T107/54	Confidential	Decontamination of Personnel and Equipment.
15	A.W.R.E. T108/54	O.U.O.	Decontamination of Protective Clothing.
16	Tripartite Conference (9th) Porton (DRB.54/10277)	Confidential	Item 3, Radiological Defence. U.K. Requirements for Radiac and Protective Clothing.
17	A.W.R.E. T111/54	Confidential	Decontamination of Beta and Gamma Emission from Contaminated Paint Surfaces.
18	British Journal of Applied Physics, Supplement No. 3 25 1941 (1954)	Unclassified	Adhesion of Dust Particles.
19	A.E.R.E. HP/R.371, 34 (1951)	Confidential	Some Engineering Aspects of High Efficiency Dust Collection.
20	Journal of Heat and Vent. Eng.20, 35-70, 1952	Unclassified	Fibrous Filters for Fine Particle Filtration.
21	A.E.R.E. HP/R.1495	Unclassified	Derivation of Maximum Permissible Levels of Contamination of Surfaces by Radioactive Materials.
22	A.R.D.E. Memo.AR.575/01	Secret	The Effect of Nuclear Irradiation on Explosives.
23	A.W.R.E. Report O-33/57	Official Use only.	The Effect of Gamma Rays on Record Film. Interim Report No. 1.
24	A.W.R.E. Report O-4/58	Official Use only	The Effect of Gamma Rays on Record Film. Interim Report No. 2.

U.S. Reports DAMAGE TO MATERIALS: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
9	U.S.A.Fed. C.D. Advisory Bulletin No. 73 (Home Office CD.5757)	Unclassified	Clothing for Protection Against Nuclear and Thermal Radiation.
10	U.S.A.N.Y. Naval Shipyard Mat.Lab. Project 5046-3 Part 38 (DRB 54/5252)	Unclassified	Report of Investigation of The Resistance to High Intensity Thermal Radiation Afforded by the Application of Water-soluble Flame Retardants.
11	U.S.A.N.Y. Naval Shipyard Mat.Lab. Project 5046-3 Part 36 (DRB 54/5253)	Unclassified	Optical Transmittance, Reflectance and Absorptance of Materials.
12	U.S.A. Calif Univ. Dept. of Meteorology (DRB 54/11197)	Unclassified	Tables relating to Rayleigh Scattering of Light in the Atmosphere.
13	J.App.Physics, May, 1956	Unclassified	Transient Thermal History of a Slab.
14	Vita-Var Corporation Quarterly Reports 1954 TIL Nos. P.55101, 55102 55103.	Confidential/ Discreet	Investigation of Protective Coatings to decrease the Vulnerability of Aircraft to Thermal Radiation.
15	Vita-Var Corporation Bi-monthly Progress Reports, 1955 TIL Nos. P.59514 and P.59515	Confidential/ Discreet	Investigation of Protective Coatings to decrease the Vulnerability of Aircraft to Thermal Radiation.

U.S. Reports DAMAGE TO MATERIALS: Thermal Radiation

No.	Originator and Reference	Security Classification	Title
16	U.S. Naval Radiological Defence lab. 1957 Tri-partite Conf. Paper No. 14	Unclassified	Ignition of Combustible Materials. Plum.
17	A.F.S.W.P. 845 Materials Laboratory (M.O.D. Ref. No. 75)	Unclassified	Method to Improve Optical Characteristics of the Black Polythene Skin Simulant. (1955) Project NS.081 - 01. 25 March, 1955.
18	W.A.D.C.54-103 (M.O.D.Ref. No. 253)	Unclassified	Behaviour of Magnesium Fibre Glass Panels subjected to Thermal Radiation.
19	Westinghouse Engineer 1954. Vol.14. Pages 147-157.	Unclassified	The Control of Radiant Heating by Surface Finish. Leedy, R.N.
20	U.S. Airforce Project Rand Report R-147, June, 1949.	Restricted/ Discreet	Short Time Creep Data for Metals at Elevated Temperatures.
21	John Wiley 1950.	Unclassified	Heat Insulation. Wilkes, G.B. (Book)
22	Department of Chemical Engineering, Massachusetts Institute of Technology, 1952. M.Sc.Thesis.	Unclassified	Analytical Study of Flame Initiation. Lawrence, E.K.
23	Fuel Research Laboratory, Massachusetts Institute of Technology Technical Report No. 2.	Unclassified	Thermal Damage Initiation in Organic Materials. Gardon, R.

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No.	Originator and Reference	Security Classification	Title
1	I.R./465 D.S.I. Translation 219, 4 pp. November, 1956. A.A. Predvoditelev, B.A. Smirnov, Vestnik. Moskovskogo Universiteta, (3), 51-55, March, 1956. U.S.S.R.	Unclassified	The Creep of Aluminium Under Dynamic Loads.
2	I.R./760.D.S.I. Translation 395, 1 p. April, 1958. L.F. Vyereshchagin, Nauka i Zhizn, (12), 1957. U.S.S.R.	Unclassified	Super-High Pressures.
3	I.R./824. D.S.I. Translation 450.Sept.1958. Ye. G. Dolmatov and I.I. Sitnikov. "Zavodskaya Laboratoriza" 1958 No. 5 pp.629-631	Unclassified	A Method of Measuring the Speed of Plastic Flow of Steel under Explosive Tension.

U.S. Reports DAMAGE TO MATERIALS: Thermal Radiation

(Note: For Certain Aviation Materials see 7.3)

No.	Originator and Reference	Security Classification	Title
1	U.S.N. Res. and Dev. Div. Bur. of Supplies & Accts. SRI Project 872	Secret	The Economics of Protective Clothing for Naval Personnel as a Defence against Thermal Effects of Atomic Weapons.
2	U.S. N.Y. Naval Shipyard Mat. Lab. Project 5046-3 Part 21	Confidential/ Discreet	Report of Investigation on Reduction of Thermal Damage by Means of Brom-poly TAP and Aminophosphorous Resins.
3	U.S. Univ. of Rochester UR.354	Unclassified	Protective Qualities of Fabric Expressed by a Protective Index.
4	U.S. Univ. of Rochester UR.353(P.49005)	Unclassified	Evaluation of Black Polyethylene as a Skin Simulant under Fabrics Exposed to Thermal Radiant Energy.
5	U.S.N.Y. Naval Shipyard Mat.Lab.Proj.5046.3 Pt.56. Final Rpt. NS081-001	Unclassified	Critical Thermal Energies of Plastic Radome Materials.
6	U.S. Univ. of Rochester UR.355 (P.50376)	Unclassified	Influence of Exposure Time and Irradiance on the Thermal Protective Qualities of Two-Fabric Assemblies.
7	U.S. Dept. of Army NC-415-55		Tech. Progress Report, 1 Jan.-31 Dec., 1954. Thermal Effects on Clothing, Multilayers, etc.
8	U.S.A./M.I.T. Fuels Res. Lab. Tech. Rep. No. 3 (CD.7399) (M.O.D. Ref. No. 29)	Unclassified	Temperatures Attained in Wood Exposed to High Intensity Thermal Radiation.

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